METRO-HAUL

"Optics Research for Future Smart Networks and Services"

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Introduction

Infrastructure projects on a national or international scale are a rare occurrence, due to their size, cost and complexity. Historical undertakings such as the construction of a comprehensive rail network, the telegraph network, sewage systems, the electrical grid and water supplies are just a few examples of the many large-scale projects that have been completed over the last 150 years. However, the 21st century has seen the start of arguably the most ambitious infrastructure project yet undertaken: the wide-scale deployment of national access optical fibre-based telecommunications networks across Europe.

This is a project that will present several unique challenges. First and foremost, the network architecture design will have to endure for 100 years or more. The cost associated with a European-wide fibre build is hard to determine but can be estimated to stretch into the hundreds of billions of dollars and take decades to implement. There is currently an underlying impression that most of the hard work and research objectives have already been realised when it comes to optics technology. This could not be further from the truth and there are still several critical areas to be explored. A well provisioned fibre optic network will provide the foundations upon which our connected world will be built. Optical technology will underpin 5G+ networks, provide consumer broadband, support future smart cities and provide connectivity for both critical and non-critical IoT applications. It is also important that ways are found to integrate these different strands seamlessly into a global, standardised network.

Future provisioning of the network will also present a problem, mainly due to the rapid development of optical technology. It is a reasonable assumption that the current fibre installation will need to be able to adapt to multiple incoming, disruptive technologies, many of which are still to be realised. Component cost is still extremely high in some applications, which is prohibitive to mass deployment in areas that lack the economic concentration of large cities or data centres. A concerted effort is required to ensure that collaborations between different vendors, network providers and governing bodies all move in the same direction, creating a network that is transparent and interoperable. The implementation of disruptive, data hungry technologies such as 5G, without proper provisioning, has the potential to create bottlenecks within the network. This problem will be amplified as network providers deal with continued exponential traffic growth. In addition to this, the next few decades may also see a gradual change in how we consume optical technology. In much the same way that the electronics industry moved from specialist equipment and components to a consumer-based market, optics may do the same.

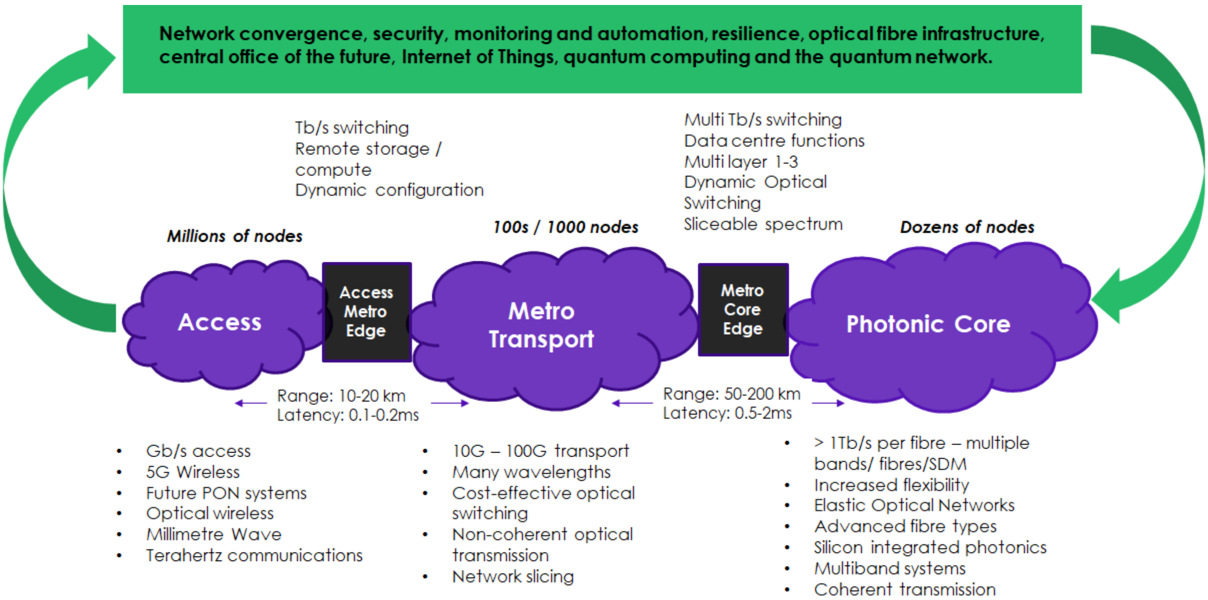
The increased awareness and emphasis on creating a “green network” has seen a drive to ensure that the underpinning technology and practices are as environmentally friendly as possible. Creating a clearly defined framework to achieving a “green network” structure is vital to ensuring future builds are not constrained or prohibited by environmental regulations. Ensuring that the network is energy-, heat- and space-efficient, whilst approaching a carbon neutral status, will be a high priority for the future.

We intend for this paper to serve as a framework to gather together the many different strands of optical research that underpin the network. We aim to provide a concise introduction to the current status of each topic and present the case for the need for continued investment and further research.

End to End Network Overview

Despite the geographical constraints of different European countries, a common network architecture is useful to help frame individual topic areas. A core network comprising a minority of key nodes provides the backbone, supporting high capacity data transport links up and down the country. This feeds into the metro layer which interconnects the core and access and increasingly providing edge data centre functionality. The access network is then responsible for the final drop, bringing connectivity to homes and businesses.

Figure 1 provides a detailed overview of a typical end-to-end network, encompassing all the different areas. As seen in fig.1, optics glues together the various network domains: access, metro and core, creating and supporting the reliable, high capacity, low latency network to which we have become accustomed. In addition, optical technology underpins the various areas that support the network and provides access to Data Centre functions such as edge compute and storage. The figure itself illustrates the wide range of issues and technologies that arise from this, and these will all be explored in this report.



Section 1 will look at the technologies that are present across all areas of the network and are instrumental in the running and maintenance of a national telecommunication infrastructure. Section 2 will focus on core technologies, section 3 will look at metro technologies and in section 4 we will look at access technologies. Section 5 will address technology that relies on the entire network to function. Most technologies are not solely specific to a single part of the network, but rather straddle two, if not three, different areas. For the sake of simplicity, we will assign each technology based on the area we assume it will have the most noticeable impact.

Section 1 - Network Control and Orchestration

The telecommunications network has evolved to underpin all the world's fundamental services and, as such, has been elevated to a high level of complexity. As the population becomes used to a high standard of coverage, it is important to ensure that the infrastructure that supports the end-to-end network is ready to cope with the continuous growth of data consumption. This section will look at ways to streamline the delivery and management of data and how to best ensure the highest QoS across the network.

Network IT Convergence

What is it?	Implementing more and more network functions in data-centre infrastructures within the Network Function Virtualization (NFV) framework is a game changer, with respect to how networks are designed and operated. These processes must now jointly address the IT, IP and transport stratums of the network in a holistic view. For example, where the data centres are placed and how NFVs are instantiated there, is tightly coupled to where the optical and IP infrastructure is planned and network resources are allocated. The SDN framework for network control should now extend its reach from multilayer IP-over-transport network, towards the IT&IP-over-transport paradigm.
Scale of impact?	All network segments, starting from metro networks and reaching the access as the edge is expanded.
Time to impact?	0 – 5 years for early impact, potentially reaching the access in 5-10 years.
Comparison with current solutions?	Current optical networks are designed & operated partially in joint optimization with the IP part, while the data-centre & IT stratum is dealt with independently, in general by a completely different department. This is a source of major inefficiencies in design and operation. As an example, network-IT convergence is the cornerstone for the new network resilience strategies where layers collaborate to survive in the most economically efficient form: e.g. reallocating NFVs, IP recovery schemes and optical dynamic restoration can now be combined to address a global service-level resilience goal. Additionally, network-IT convergence is the framework to enable true energy efficiency optimization, i.e. accounting for all the IT and network stratums. Optical technologies are the well-known golden choice in terms of energy per bit, with one, two or even three orders of magnitude advantage compared to power hungry electronics in the IT and IP/MPLS network segments. Green networking goal can only be achieved by a research that expands the application of optical technologies in the global network.
What kind of research?	Research needed in network control and orchestration, as well as network design, including clean-slate views.
EU impact?	Essential for addressing the giant leap in complexity in the networks, as IT stratum becomes an active and crucial component of network functions. Will provide technology leadership for multiple EU-based companies in the different segments involved.

Monitoring and Automation through AI/ML

What is it?	The control and management of optical networking infrastructures will increase in complexity with the introduction of several new degrees of freedom (in the context of EONs) and the expected developments in the framework of 5G networks. As the complexity and volume of data increases, a prompt response to variable network conditions while ensuring full availability and optimization of network resources will be a key challenge for operators. Nonetheless, the networking infrastructures generate an enormous amount of data that can be exploited together with novel machine learning (ML) based solutions to facilitate network operation and predictive maintenance. In this regard, monitoring and data analytics can offer unprecedented opportunities to transform the current infrastructure towards a fully autonomous one where the network can operate up to its limits with a high level of reliability and efficiency.
Scale of impact?	All optical networking segments can benefit from this development.
Time to impact?	0 – 5 years for early impact, but these systems will develop and mature over the next 15 years, to become a staple of networking systems
Comparison with current solutions?	Current networks require human-based interventions and manual processes in their design and operation, which make it difficult to exploit their full capacity. The future networking infrastructure based on monitoring and data analytics will circumvent most of these manual processes and contribute significantly to repair-time reduction, maintenance cost, and extra revenue due to the realization of low-margin operation of the networks.
What kind of research?	Research needed in the components (e.g. for monitoring devices), systems (e.g. monitoring enabled systems), networks (e.g. close-loop network operation), and control layer (e.g. telemetry and data analytics platforms). In addition, it would need research on secure platforms for network data sharing and trading among telecom operators and vendors for the development/validation of data-enabled algorithms.
EU impact?	Essential for carrying huge future capacity around Europe's member states. Will provide technology leadership for multiple EU-based companies from component manufacture through to complete system vendor. It can create new markets for telecom operators and provide opportunities for SMEs and start-ups within EU to develop data-driven solutions for such a new ecosystem.

Security

What is it?	The world is increasingly aware of the need for security in telecommunications, prompting the design and implementation of increasingly advanced techniques. Optical fibre itself is not secure and can be physically hacked with simple tapping devices. Furthermore, optical fibres carry not only data that needs to be ultra-secure, but also carry control systems managing critical infrastructure such as power plants and entire network operations. In recent years, security has become a problem for the physical layer, especially when this carries a wide number of separate channels, not all of which have dedicated encryption.
Scale of impact?	All network segments, starting from core and metro networks and reaching the access as the edge is expanded. Potentially different solutions would apply to the different segments, according to risk profile and cost to implement.
Time to impact?	0 – 5 years for early impact, potentially reaching the access in 5-10 years framework.
Comparison with current solutions?	Current cryptography is deployed often at the application layer using techniques such as Public Key Encryption – e.g. RSA. This will be rendered obsolete with the advent of quantum computers, and there is a world-wide endeavour to find replacements. Although there is hope for mathematical encryption, this shouldn't prevent research into physical layer solutions, which can potentially protect an entire optical fibre. Layer 1 – layer 3 encryption solutions are being used to protect site-to-site communication for mission critical applications, yet most solutions are not quantum-safe today and may not provide the necessary agility for in-field upgrades
What kind of research?	Research into the wide range of techniques for ensuring security, including detection of tapping, physical layer security (e.g. ways to protect data at the fibre level) as well as quantum security (such as QKD) and links between quantum and post quantum (classical) cryptography. There is a need for combined security and networks research. Additionally, there needs to be a holistic approach which includes the client layers such as 5G or optical access. In this topic area, there is a need for multi-disciplinary research including the security community.
EU impact?	EU-based innovation should lead to new companies specialising in this area which is expected to become much more critical in the future. It is important that the EU develops its own expertise in this field to isolate itself from dependencies on other national players. All EU nations need to focus increasingly on the security of their national critical infrastructure.

Resilience

What is it?	Optical networks resilience is a keystone in the global network service resilience goal, where IT, IP and optical transport segments must now cooperate in a holistic view, and dynamic optical reallocations are the only path for cost-effective resilience. Novel AI/ML techniques will be critical in this role. AI/ML will exploit the vast optical monitoring data to provide a characterization of the in-plant optical physical layer, an unavoidable requisite to be able to dynamically validate reconfigurations like optical re-routing, or re-adjustments of modulation and bit rates. AI/ML-assisted operation of optical networks will also enable preventive fault tolerance, e.g. detecting patterns that warn about incoming failures in transponders or fibre links. Disaster resilience seen at the service level is an imperative research field, which will be strongly impacted by the joint IT, IP and optical holistic view. Indeed, a reliable layer coordination, potentially based on a minimum signalling exchange, opens the door to new opportunities to address disaster resilience, reallocating services and resources in all the layers.
Scale of impact?	Core, metro and access will all benefit from an increased level of resilience. However, with the large quantities of data handled by the core network and its future prominence in supporting many future integrated appliances, the core network will be a priority for improved resilience.
Time to impact?	0 – 5 years for early impact.
Comparison with current solutions?	Current optical networks resilience is designed, at best, jointly optimized with the IP network. This process should be expanded to include NFV allocations and IT infrastructure, forming a more holistic view. In this context, AI/ML techniques should be exploited to break the barrier that now limits dynamic optical reconfiguration. There exists very limited capabilities today to pre-validate the optical quality of reception under network reconfigurations and to predict optical system failures.
What kind of research?	Research needed from components to systems and networks.
EU impact?	Essential for economic feasibility of the large optical infrastructure deployments in which 5G/6G networks in Europe are founded. Through enhanced resilience we can ensure a higher quality of user experience

Section 2 – Core

The core network is a collection of nodes and links that serves as the primary method of data transportation and connectivity across an entire country or region. This in turn provides a backbone structure that is required to connect a range of devices, such as routers, hubs and switches. This creates an ordered hierarchy that is critical to the central connectivity of the entire edge-to-edge network. Due to the exponential increase in data consumption as we move towards a more connected society, the core network is increasingly called upon to deliver higher bandwidth and more dynamic flexibility, making it a focussed area of research. Outlined in this section are some of the key areas that we feel have an active role to play in building a network with both the capacity and flexibility to meet future demands.

Elastic Optical Networks

What is it?	Future optical networks will make more flexible use of the optical spectrum available together with transponders offering a wide range of dynamic modulation formats. The network switches and other components will adjust to make bandwidth available as services grow. There are many open questions here, related to the optimal flex-grid spectral units, how to utilise flexible spectrum and transponders at the same time, how to avoid fragmentation, the need for dynamics in the optical layer, protection questions and interaction with higher layers such as IP. A deep understanding of EONs will be essential as optical transport moves into multiband transmission, where the potential for flexible networking is increased yet further.
Scale of impact?	All core optical networks in the future, and potentially metro networks as capacity grows.
Time to impact?	0 – 5 years for early impact, but these systems will develop over the next 15 years, especially as C+L band systems and even broader waveband systems come within reach.
Comparison with current solutions?	Current optical networks use a fixed wavelength grid with fixed modulation format transponders. This is an inefficient use of bandwidth and prevents the use of new transponder types.
What kind of research?	Research needed from components to systems and networks. Components include both the transceivers as well as flexible optical switches and the architectures involved. system performance can now be very dynamic, responding to changes in the link; the impact on an overall network of individually fluctuating links is complex, requiring research at all levels for most impact.
EU impact?	Essential for carrying huge future capacity around Europe's member states. Will provide technology leadership for multiple EU-based companies from component manufacture through to complete system vendor.

Advances in Fibre

What is it?	The intrinsic bandwidth capacity of standard SMF optical fibre is now a system limitation, so SDM technologies to increase capacity, via fibre arrays and fibre bundles featuring multicore geometries, are required to meet the ongoing exponential data explosion. In addition, new optical fibre designs (microstructure, hollow core fibres etc.) featuring novel propagation characteristics (e.g. low non-linear effects, high group velocity, wide bandwidth etc.) could allow longer distances between amplification, support low latency services and enable all-optical signal processing functionalities.
Scale of impact?	Increased low cost capacity enabled by SDM and massive parallelism would impact access and metro networks significantly lowering the cost per bit of the network. Low latency networks enabled by hollow core fibres would enable new applications that are not feasible today for example remote medical care and connected and autonomous vehicles. Exchange building fibre connectivity is also a rich avenue for applications.
Time to impact?	The imminent increase in data consumption and the strain this will put on the network is well known, however disruptive fibre technologies must pass stringent standardisation before being used in the live network. Therefore, it is realistic to assume that there is a 5-10 year wait for implementation.
Comparison with current solutions?	Current methods to enhance capacity use wavelength (WDM), time (TDM), polarisation (PolMux), advanced modulation formats (M-QAM, OFDM) each have their relative advantages. SDM offers quadratic (i.e. super-linear) scaling improvement of capacity with multicore radius. Silica based fibre has an inherent latency and cannot propagate high optical powers without inducing non-linear effects, neither of these problems are as prominent in hollow core fibre.
What kind of impact?	For SDM splicing between multicore bundles, multicore coherence, spatial parallelism of components and cross-talk performance between cores. For hollow core fibre reduced attenuation is required (e.g. surface roughness, photonic bandgap confinement, uniformity of microstructure), whilst the expansion of bandwidth beyond 1.6 µm to 2.4µm will be key to increase capacity. In addition, all fibre types will benefit from on-the-fly all-optical signal processing designs & methods.
EU impact?	EU universities and industry are already global leaders in these advanced fibre technologies, which will support new component, system and network architecture designs.

Silicon Integrated Photonics

What is it?	Silicon (Si) integrated photonics unites the large-scale fabrication benefits of CMOS microelectronics and photonics, to create a cost-effective, seamless electronics/photonics photonic integrated circuit (PIC). This technology can serve as a platform for fully integrated information processing, storage and transport.
Scale of impact?	All on-chip, chip-chip, LAN networking technology solutions, where local processing and short-distance transport of data is required can benefit from Si photonics. They have the potential to create a consumer optics industry, where optics scales with volume in the same way electronics has done for decades.
Time to impact?	5-15 years – still a medium-long term technology solution, but with tremendous potential for cost reductions and CMOS VLSI technology transfer.
Comparison with current solutions?	Fully integrated solutions could take over from existing hybrid approaches which are intensive on assembly and testing and less able to scale to high volumes. Hybrid technology platforms based on silica (SiO), InP, GaAs/AlGaAs, polymer technologies require separate manufacturing and integration onto CMOS Si substrates, in order to achieve an equivalent 'seamless' electronic/photonic function.
What kind of research?	Photonic nanowires, in-out coupling, attenuation reduction (surface roughness). Active operation (direct bandgap engineering) for light emission/detection, Si-based photonic bandgap (PBG) and photonic crystal (PhC) light control, waveguiding and optical processing.
EU impact?	Important for future European leadership in PIC fabrication, semiconductor industry electronic/photonic VLSI device manufacturing, to provide European technology leadership in devices, components, and subsystems.

Multiband

What is it?	Network operators face a strong growth of data traffic in their optical networks, leading to a continuously shrinking reserve of dark fibres until the point where links will reach the limit of their capacity in the optical C-band. Exploiting optical bands beyond the C-band to increase transmission bandwidth is one way to further increase the capacity of single-mode fibre (SMF) links. Currently, C+L band systems are seeing deployments with operators worldwide. In principle, the bandwidth for data transmission can be further increased to span the whole available low-loss window of zero-water-peak ITU-T G.652D fibres, reaching over a total of 365 nm (~53.5 THz) from 1260 nm (O-band) to 1625 nm (L-band). This will provide approximately 10× the bandwidth of current C-band systems. In the long term, the multiband approach can also be coupled with spatial multiplexing for ultimate fibre capacity.
Scale of impact?	All submarine and core optical networks requiring point-to-point capacity enhancements, and metro networks as bandwidth demand continues to grow.
Time to impact?	In 4 years, we expect to see utilisation of the S-band in conjunction with the C+L bands, with a desire to see full utilisation of all available bands in an additional 10 years, massively increasing the available bandwidth.
Comparison with current solutions?	Current C-band solutions focus on maximizing spectral efficiency by advanced coded modulation schemes, fibre nonlinearity compensation, and general techniques to enhance the signal-to-noise ratio (SNR). However, the total capacity scales only logarithmically with SNR, while it scales linearly with the additional bandwidth provided by multiband systems. Furthermore, the spectral efficiency in C-band systems has almost reached its theoretical limit. Therefore, it becomes increasingly difficult to further increase capacity in the traditional C-band, making the decision to utilise other bands seem increasingly like the logical choice.
What kind of research?	Multiband photonic components (tuneable lasers, modulators, coherent receivers, wavelength-selective switching elements, optical amplifiers), multiband network and system modelling and planning, fibre nonlinearity mitigation in multiband systems.
EU impact?	Network operators will be able to scale their deployed fibre infrastructure with capacity demand, thus postponing expensive new fibre deployments. European system vendors will greatly enhance their market position worldwide by being able to offer multiband upgrade paths to their customers. European photonic component vendors already have strong products and expertise in the required technologies and could strengthen their market position. In this field, the industry is supported by key actors in the European academic sector, which already contributed significantly to the multiband trend in the worldwide scientific community.

Coherent Transmission

What is it?	The need for higher network capacities and the progress in CMOS technology have made coherent transmission the de-facto standard in optical long-haul and sub-sea networks. The use of DSP-enabled (digital signal processing) coherent receivers allows us to filter out wavelength channels, to digitally compensate transmission impairments, and to increase performance and spectral efficiency. Coherent technology has also alleviated the need for optical dispersion compensation and thereby greatly simplified network planning and operation.
Scale of impact?	While coherent transmission will continue to evolve in long-haul and sub-sea areas, it has already started scaling down and rapidly conquering new territory in the metro, access/aggregation and the data centre domains. In a not-too-distant future, it can be imagined that all optical site-to-site communications and demanding intra-office applications will use coherent transceiver technology.
Time to impact?	0 – 5 years for early impact, but there will be continuous development over 15+ years.
Comparison with current solutions?	While direct detect transmission is still being used at lower data rates, coherent transmission will displace these solutions in the WDM domain as data rates increase and cost-efficiency of coherent solution improves.
What kind of research?	Increase of symbol-rates, advanced modulation and signal shaping methods, efficient multi-channel integration, non-linearity compensation, approaches to radically reduced cost and power to push coherent solutions for cost-sensitive and moderate data rate applications, channel estimation and auto-configuration, optical wide-band and multi-band operation, related system and network architectures.
EU impact?	European industry and academia have pioneered coherent transmission and its first commercial implementation around 2010 and first generations of the technology are deployed in all service provider networks. This position of strength should be leveraged to actively develop the "coherent future" in and for Europe.

Section 3 – Metro

This part of the network has the potential to become a significant bottle-neck in the future. The key requirements will be for very high bandwidths, but over limited distances and with emphasis on low cost. As Edge Compute becomes more prevalent, the metro will continue to see growth in demand for reliable, low latency transport. The dynamic nature of future 5G client traffic suggests a dynamic, optically flexible metro if possible, with resulting challenge around both physical and control planes.

Cost Effective Optical Switching

What is it?	Metro networks sophistication and scale make them critically sensitive to cost and demand cost-effective optical switching alternatives. Filterless optical switching architectures are extremely simplified and cost-effective options, that have shown their place in the metro network, creating a sweet spot from a techno-economic point of view. The incorporation of multi-band networking and space multiplexing for expanding the optical metro capacity is putting pressure into novel active switching architectures. This then allows both spectrum and space multiplexing to be applied, in a cost-effective manner. Additionally, disaggregation and white-box initiatives where the line system and optical switching are decoupled from the transponders, and their interfaces are opened, is a driver towards revitalizing the market and a potential to cut down costs.
Scale of impact?	Metro networks, in synergy with the core.
Time to impact?	0 – 5 years for early impact, but these systems will develop over the next 15 years.
Comparison with current solutions?	Metro networks are costly because of the optical switching CapEx, and deployment and operation time and costs caused by the long-time frames needed for new deployments, and vendor lock-in. Alternatively, operators choose not to use optical switching and then suffer from a lack of flexibility to adjust the network according to varying traffic demands.
What kind of research?	Research needed from components to systems and networks.
EU impact?	Essential for economic feasibility of the large optical infrastructure deployments in which 5G/6G networks in Europe are founded.

Non-coherent optical transmission

What is it?	Non-coherent optical transmission uses direct (intensity) detection instead of a DSP-enabled coherent receiver. In applications where power consumption and a small footprint are much more critical parameters than spectral efficiency and high line rates, non-coherent transmission will continue to play an important role. This is especially true when operating near the zero-dispersion wavelength of the transmission fibre, where low effort analogue equalization and simple frontend architectures are adequate and make non-coherent approaches hard to beat.
Scale of impact?	Use in access and intra-office applications, attractive for Silicon-Photonics integration, e.g. in form of chiplets on next-generation switch ASICs.
Time to impact?	0 – 5 years for early impact, but continued influence of the next 10+ years.
Comparison with current solutions?	Currently many operators still use 10Gb/s systems, but traffic growth is putting these under pressure. Coherent options might be too expensive in this space, but non-coherent needs to move beyond 10Gb/s to 25Gb/s, 50Gb/s and beyond. Lower modulation losses enable higher launch powers in passive applications than with coherent interfaces. Easier multi-channel integration due to simpler structures, smaller sizes and lower drive power requirements.
What kind of research?	Increase of symbol-rates, advanced modulation methods, efficient multi-channel integration, approaches to radically reduced cost and power, auto-configuration, related system and network architectures.
EU impact?	Volume of direct detect interfaces is orders of magnitude higher than for coherent interfaces. Has been an area of very active research in Europe in the recent years. Results can be leveraged in definition and implementation of next-generation direct detect solutions.

Network Slicing and Software Defined Networks (SDN)

What is it?	5G network applications will come in many shapes and sizes, all with different requirements in terms of latency, bandwidth etc. The ideal way to manage all of this is to be able to configure network slices, each tuned to the individual slice KPIs. Some of these applications will require intensive compute and storage functionality, potentially supplied by network functions virtualised somewhere in the network. Therefore we require a new breed of SDN-based orchestration, working across domains, to do the full management of this new 5G-based networking paradigm. Without this the network will either not be able to provide the necessary resources for a given application or we will have to massively over provision the network, resulting in considerably higher cost and energy usage. Ideally a slicing solution will be fully dynamic, with complete slices being set up and torn down as required.
Scale of impact?	Given the inevitable migration to 5G across Europe, this research will ultimately be universally applicable on a vast scale. In addition, slice management will be used increasingly to utilise operator resources at the edge of the network.
Time to impact?	Given the software-based nature of much of the research envisaged here, early benefits could be felt within 5 years. The main impact will be felt when applications come on stream that take full advantage of the 5G infrastructure, which might be more in the 5-10 year timescale.
Comparison with current solutions?	Currently, concepts such as end-to-end slicing for 5G are not supported in networks. Crude approaches currently would be to set up static services for a key application – with nailed up transmission (e.g. a wavelength), storage and compute resources tailored for that application. This isn't scalable but is all that is possible without a fully orchestrated solution.
What kind of research?	Predominantly this would involve software-based networks research, developing SDN concepts through to full orchestration. Additionally, there will be research into data monitoring techniques and collation of many disparate streams of information to aid overall decision making. This would likely involve Machine Learning type approaches. The research also would cross over domains, linking fixed and wireless network research tracks.
EU impact?	Over the previous 5 and more years, the EU research program has focused intensively on building the necessary building blocks for 5G, including the development of applications and the infrastructure and management needed for them to function. This proposed research would serve to enable these applications to be fully managed whilst maintaining an efficient overall network with carefully managed resources.

Section 4 – Access

The access network holds the most potential financial value to telecoms providers, providing the "last mile" of connectivity to users, in both residential and business markets. Providing a high speed, high capacity, reliable QoS is essential to maintaining continued investment in infrastructure development. Customers' data requirements are constantly increasing, fuelled by a list of ever-expanding connectivity options. In order to manage this expected growth, it is important to look at novel and innovative methods to provisioning the access network. In this section we outline several solutions to increasing link capacity within the access network.

Optical Wireless

What is it?	Final-drop is always the most cost-sensitive part of a telecoms network, so that cheap, high-bandwidth solutions to achieve reliable access connectivity between end-users (fixed and mobile) and the access-metro-core network are required. Free-space, direct line of sight (LoS) and point-to-point wireless optics offer desired capacity, straightforward deployment and a complementary approach to other (fixed-line and RF wireless etc.) access technologies to facilitate final-drop redundancy/restoration/ robustness/reliability.
Scale of impact?	Offers high capacity, low latency connectivity links to a variety of end users, providing an alternative, cost efficient solution to normally expensive fibre deployments. It can be used to facilitate several niche deployment scenarios. Use cases include providing backhaul for 5G cells, disaster recovery for damaged links, track-side communications and top-of-rack communications.
Time to impact?	0-5 years – Optical Wireless leverages off developments in laser/LED technology and guided-wave (fibre) telecoms, and so can already enjoy early impact.
Comparison with current solutions?	Fibre-to-the-Building (FTTB), Wi-Fi (RF, microwave, mmW, THz) technologies all offer alternative approaches for Final-Drop; each with their own advantages, according to topology, topography (geographic location, user densities, difficulty of access), reliability/restoration requirements, end-user SLAs and pricing points.
What kind of research?	Spatial & technology diversity (to ensure continuity of service due to LoS impacts, e.g. fog/mist, precipitation, environmental pollution); robust telescope optics or high-power lasers with cheap optics, adaptive optics to compensate for variable atmospheric conditions; lambda/frequency muxing to increase bandwidth capacity; indoor solutions (e.g. integration with ceiling mounted lamps).
EU impact?	Already European leadership in this area (e.g. Glasgow Uni, HHI Berlin) with lighting and laser/LED manufacturers, and specialist system vendors, e.g. specialising in train/tram/vehicle-to-shore communications.

Future PON Systems

What is it?	Passive Optical Networks are the natural choice to provide FTTP, for both commercial and residential users, cost-effectively servicing the growing need for scalability, flexibility and capacity within the access network. GPON, XG(S)-PON or even HS-PON don't provide sufficient bandwidth in the long term for expected future capacities from 5G MU-MIMO antennas, so it is critical to consider higher capacity PON systems and the role that they can play.
Scale of impact?	As we move towards a datacentric society, where a reliable connection is considered a basic living standard, more countries are prioritising the need to establish fibre connectivity to the home. A PON architecture is the logical answer to this application and it may also be for future mobile applications. The proliferation of 4G, 5G and smart devices is also driving demand for investment in infrastructure leading to increased density of cell sites and X-haul (Back-, Mid- and Front-) capacity. Future PON systems should play an important role as part of the infrastructure as it is most effective at simultaneously supporting low and high bandwidth connections with bursty traffic from the service applications.
Time to impact?	Disruptive, data hungry technologies such as 5G, autonomic industries, data centres etc, will fuel the need for higher capacity optical access. Fibre infrastructure deployment is a lengthy process, but a proactive approach will be required to keep pace with increased demands over the coming 5-10 years.
Comparison with current solutions?	G-PON & XG(S)-PON are the established first choice for FTTH deployment strategies but have insufficient capacity in the medium term. New PON technologies for fibre to the antenna (FTTA) should be interoperable with FTTH technologies such as G-PON, XG(S)-PON, NGG-PON2 and HS-PON. It would also need to provide a significant increase in bandwidth, whilst keeping equipment and operational costs limited. Future PON technology will have significant use case applications for 5G transport, especially as densification leads to a vast increase in the number of small cells and will also be used for businesses and high-end residential customers. Another big challenge for future PON systems is machine-to-machine-communications (MMC) requiring high capacities with ultra-low latencies and increased resilience.
What kind of research?	Physical layer technology - how to increase the line-rate and attain the high-power budgets (~35dBs)? Is coherent optical transport useful in the access or too expensive? Is it possible to develop pluggable ONUs and OLT ports? Do we need new opto-electronic materials? What could be done to lower the investment to produce integrated photonics? Control layer technology - Multi-domain/multi-layer network research with 5G + PON integration and overall control and orchestration. How should or could resilience be implemented? Service layer – how bursty is the traffic from current and future mobile applications? How should QoS be implemented? Is it realistic to expect service latencies around ~1ms roundtrip? Distributed vs Centralised Service Application Nodes?
EU impact?	In the next 20-30 years, Europe will be connected directly to optical fibre, this activity will cost $100s bn. European Research need to ensure that this is a once in a lifetime infrastructure investment and it is successful for European society.

Terahertz Communications

What is it?	A point to point, high bandwidth (several 100 THz), highly directional communication channel using parts of the electro-magnetic spectrum, from 0.1-30 THz. Its range is dependent on atmospheric conditions and frequency. Low frequencies (0.1 – 1THz) can provide range of a few kilometres, frequencies above 1 THz will probably only be useful for picocells. THz frequencies are also a 'natural' frequency associated with much quantum computation and processing, e.g. using graphene substrates (which has plasmon natural resonances at THz frequencies). Thus, THz communications forms a convenient interface between photonics and quantum processing. THz can be either free-space or guided (e.g. as plasmons on graphene substrate).
Scale of impact?	The lower frequency range (0.1 - 1 THz) gives a longer range which will allow high bit-rate user access in rural areas, ad-hoc wireless networks, wireless fibre extension, short reach indoor communication or fixed/mobile wireless access. Could be useful for 5G micro-cell connectivity. Also applicable for cheap, convenient, and large-scale integrated quantum processing, storage and qubit transport; acting as the ubiquitous interface between classical photonics and quantum technologies.
Time to impact?	Estimated at 3-6 years in the lower frequency range, where purely electrical means for signal generation and detection are available. It is 10-15 years for the higher frequencies, leveraging off developments in QCL technology for THz radiation generation – before the advent of QCLs, high frequency THz radiation required bulky & expensive equipment to generate.
Comparison with current solutions?	THz Communications offers significant bandwidth, much of which exists as currently unallocated spectrum. It is also highly directive, making it easier to align compared to optics. However, its vulnerability to atmospheric attenuation and relatively low power sources, limit its range and functionality.
What kind of research?	THz waveguiding, confinement, modulation (amplitude/phase/frequency), high-temperature (i.e. room temp) QCL operation, efficient THz detectors, Electrical THz generation and detection, Baseband signal processing for the THz channel.
EU impact?	There is already considerable European leadership in the THz space (UK, Switzerland, France, Spain, Germany) with research at universities and research institutes. There is excellent potential for global leadership in THz devices/subs-systems/systems manufacturing, and interfacing with the nascent quantum computing industry.

Section 5 – Closely Related Topics

There are many areas of research that encompass the entire end to end to end network and therefore cannot be conveniently placed into one of core, metro or access. By their nature, these areas tend to look at large scale projects; ubiquitous next generation mobile coverage; quantum safe cryptography; national infrastructure monitoring; nationwide smart data sensors. The size, impact and legacy of these findings make it a critical area of research if we are to create a future proof telecommunication network, that will be of maximum use for the generations that follow.

Optical Fibre Infrastructure

What is it?	The end to end network includes tens of thousands of kilometres of fibre, exchange sites, telecoms equipment and consumer products. In order to monitor and maintain the network, proactive steps must be taken towards designing novel strategies for both fault detection and asset inventory. Fault detection may be achieved through techniques such as ground penetrating radar, data gathering to identify re-occurring trends, intelligent systems to predict points of failure within the network. This in turn will allow for savings in both CapEx and OpEx and allow for the costs associated with fibre installation and repair to be implemented more efficiently. All these measures should be combined, transforming infrastructure monitoring into a proactive rather than a reactive process.
Scale of impact?	The impact will scale proportionally with the size and age of the network. Changes to conventional topology brought on by the emergence of 5G, data centres, increased throughput, FTTH etc, will all play a part in emphasising the need for more advanced infrastructure monitoring.
Time to impact?	The deployment of large-scale fibre networks will increase both reach and density, which is required to realise the many technological advances expected over the next 20 years. Current fibre networks do not have the capacity to continue to be fit for service. Therefore, it is imperative that this future network be as flexible, interoperable and resilient as possible, in order to maximise its longevity and usefulness to future generations. The work on achieving this must begin now, if we are to keep pace with the explosive rate of connectivity growth.
Comparison with current solutions?	Current fibre monitoring is focused on core networks. Future access networks will comprise millions of separate fibre circuits and existing solutions are unlikely to scale directly. An entire, new innovative approach is required.
What kind of research?	Research into fibre monitoring, infrastructure detection, commodity/consumer optics, automation, inventory.
EU impact?	Europe will see a century-scale investment into consumer fibre access in the coming 10-20 years and these networks will need to last for 100+ years at least.

Central Office of the future

What is it?	The Central Office (CO) or Local Exchange is the communication provider (CP) building containing all the switching, routing, transmission and related equipment to enable the running of a telecommunications network. Recently, problems around the CO have built up, due to the continued exponential traffic growth, coupled to the amount of power dissipation. COs are seeing issues such as congested fibre cabling, inadequate air conditioning, insufficient electrical power availability, difficulty of releasing legacy equipment and the need to add data-centre type functionality. Coupled to this is the fact that traditional exchanges were not designed for the scale of usage seen today. Added to this, is the concern about redundancy and reliability, critical infrastructure and disaster management to cope with floods and other events. Research is required on multiple fronts to address the various challenges described here. From new types of air conditioning, optical cabling, optical switching and electrical power management and efficiency.
Scale of impact?	Currently, practical network designs must consider the limitations of COs, so this work could potentially impact on the entirety of telecoms infrastructure – many thousands of buildings, representing a vast, expensive and power-hungry estate.
Time to impact?	Five years and beyond with scope for early benefits.
Comparison with current solutions?	Current solutions have tended to build networks on top of existing networks, with very limited opportunities to decommission the legacy equipment. Fibre management has also evolved rather than been optimised, leaving COs containing a wide variety of different generation equipment. This can leave COs in a poor state and prone to failure. As current traffic growth is already placing strain on available space, power, energy consumption and temperature maintenance, we can only expect these issues to grow as we continue to build out our networks.
What kind of research?	A wide variety of research into things such as air conditioning, power optimisation / management, new cables and optical switching infrastructure, monitoring and sensing techniques, automation for maintenance tasks.
EU impact?	Many EU CPs suffer from the same issues in terms of ageing infrastructure that isn't as well designed as (for example) modern day data centres. This research is badly needed to allow them to keep pace with the ongoing exponential traffic growth.

5G + optical network convergence

What is it?	Society's insatiable demand for ubiquitous high speed, high capacity on demand data coverage has paved the way for the introduction of 5G. The current rollout will provide a significant capacity boost (greater than 1 Gb/s), ultra-low latency, reliable communications and an increase in the range and number of connected devices. This will provide new capabilities in dynamic data gathering, autonomous transport links, virtual reality smart grid and e-health, encompassing both the high and low end of IoT spectrum. To service this, a dynamic, high capacity optical fibre infrastructure is essential, complete with a fully orchestrated E2E control plane.
Scale of impact?	Cisco's Visual Networking Index (VNI) predicts that although 5G rollout is in its infancy, by 2022 connections by 5G devices will have gone from under half a million to over 422 million. From a global standpoint, 5G enabled devices will account for 3.4% of connections, but will generate 2.6 times more traffic than 4G (54% of connections), therefore generating 11.8% of global traffic. As 5G enabled devices become more prevalent, we can expect a correlated increase in data consumption on all fronts, increasing strain on the main optical backhaul networks.
Time to impact?	It would be wrong to consider the move from 4G to 5G as an overnight switch. It will take time for both devices and network infrastructure to move from 4G to 5G NSA to 5G SA. The switch to a 5G dominant landscape will be impacted by a range of physical, technical and socio-economic factors, combined with a desire to maximise the legacy 4G network. However, the benefits of 5G usage on a much wider scale are undeniable, and it seems that we are sitting on the cusp of a decade of slow, but steady, transformation.
Comparison with current solutions?	Current optical backhaul is rudimentary, assuming 10G DWDM solutions running over fixed filters - in order to keep costs down in this part of the network. Additionally, the optical backhaul is not associated with the 5G client traffic at all.
What kind of research?	Optical transmission rates will need to increase to at least 100Gb/s, but in a cost-effective way and this might involve low-cost coherent technology, or higher speed non-coherent (see separate sections on these). Additionally, there needs to be strong research on cost reduction of components such as optical filters and switches. Control plane research to tie together the 5G client layers, compute / storage DC nodes and the optical backhaul transport will be critical. There will need to be a comprehensive economic analysis of 5G deployment, with an emphasis on how the benefits can be shared between rural and urban areas.
EU impact?	The EU has invested significant funds into the establishment of 5G. for it to be sustainable, this research will help fuel the take-off of 5G, enabling services to meet their individual SLAs. Ultimately it will ensure the EU 5G networks are best in class, most efficient and cost effective.

Internet of Things

What is it?	Internet of things (IoT) has moved from a fringe technology to a core part of our consumer infrastructure in a single decade. The mass use of low-cost, low-consumption connected devices has led to unprecedented growth in the number of endpoints putting strain on the network. How all this data will get transported optically is still largely undecided. Further, the holistic control of IoT networks, with an optical layer that bridges between IoT and compute / storage capabilities will be required.
Scale of impact?	A completely autonomous, self-aware network has long been touted as the stuff of science fiction, however the benefits of widescale adoption of IoT cannot be underestimated. It is hard to imagine a situation, industrial or social, that does not or will not benefit from the efficiencies and autonomation that IoT will provide. However, it poses a problem for network providers, as they must prepare for an increase in data connections, storage and analytics, all of which will be needed to underpin the IoT revolution.
Time to impact?	IoT is already imprinted onto our daily lives and as the benefits become more apparent, we can expect a drive to a more ubiquitous service.
Comparison with current solutions?	There currently is no clear provision for IoT data transport within the optical arena, where it is assumed that all traffic will be bundled onto transport (e.g. ethernet) with no implications for the optical layer. However, as IoT data rates climb (e.g. with video services such as surveillance / CCTV) then an integrated IoT + photonic layer for (e.g.) SMART cities becomes essential.
What kind of research?	Control plane orchestration to tie together the client side (IoT devices) with transport and the edge compute functions is largely non-existent, by enhancing network automation many of the processes within the network can be made much more efficient. Additionally, there will be research into ultra-low cost, low bit rate transport and its integration into the optical layer. Finally, full city-wide 4k video security would need an ultra-high bit rate optical solution, involving transport, switching and dynamic control.
EU impact?	The EU has aspirations to be at the forefront of IoT systems. In order to do this it will need technology that doesn't hit the regular bottle necks. These can occur due to insufficient transport solutions to support the data rates and dynamics implied i.e. ultra-low latency connections from the home that in the quantitates predicted will put a capacity strain on the metro network. The social impact can also not be underestimated, with industries such as health, finance, social mobility and lifestyle all set to benefit directly from an enhanced IoT experience.

Quantum Networks

What is it?	Advances in quantum computing mean that the potential threat of decrypting many of our currently implemented classical public key cryptosystems via use of a large-scale quantum computer is becoming a very real threat. Quantum networking aims at enabling secure quantum communication and distributed quantum computing reliably between multiple users and nodes in large networks with complex topologies. Quantum repeater networks will likely implement entanglement swapping based quantum teleportation to distribute quantum information across long distances and between many nodes in complex network topologies. Such quantum repeater networks are required for distributed quantum computing, but moreover enable long-distance end-to-end quantum communication.
Scale of impact?	The need for secure communications in the advent of the cyber-security threat posed by a large-scale quantum computer is becoming increasingly urgent; namely for most critical infrastructures and service providers, the governmental and military sector, banking, health, and insurance companies, and many others.
Time to impact?	0-15 years. With respect to Quantum Key Distribution (QKD), quantum networks already have an impact to date, as a few QKD networks already exist in some metropolitan areas where they protect communication infrastructures. In a relatively short time-scale (of 3-5 years) their impact could be significantly increased if their accessibility by users and deployment in existing infrastructures were simplified. Quantum computing on the other hand is likely to be 5-10+ years away.
Comparison with current solutions?	All currently known schemes of classically distributing keys across a network are only computationally-secure, including post-quantum cryptography-based algorithms, whereas QKD resistant to any advances in computing power, be that classical or quantum. Free-space/satellite communications are also competing against fibre-based QKD solutions. Algorithmic-based post-quantum cryptography promises security against known quantum computer attacks, also with the advantage that there are no distance limitations, but the security against other unknown attacks remains an open question.
What kind of research?	Optical component technology research including photonic integration. Work on the algorithms involved and design of systems and networks involved.
EU impact?	European industry/academia is already leading in QKD and single photon devices, so is well-placed to assume global technology leadership in this area. The technological leadership is supported by the continuous standardization activities of the ETSI Industry Specification Group for QKD, which regularly

	releases updated specifications for commercial deployment for QKD in networks.

Environmental impact

What is it?	Service providers and operators are confronting new issues regarding the handling of electrical power in their buildings. This problem is exacerbated by the fact that these buildings were never designed to handle such high quantities of power. This has a knock-on effect, as traffic grows exponentially, specifications on the creation of new infrastructure is now dependent on available power as well as sufficient air conditioning. Work is now required to explore ways to reduce the amount of energy used in networks. On a more global scale, there is also pressure for network providers to consider and ultimately reduce their carbon footprint.
Scale of impact?	The telecommunications sector accounts for roughly 4% of global electricity consumption. Future EU country networks will be seriously impacted by any increase in energy requirements. This will lead to stagnation of infrastructure deployment, as buildings will become full and unable to support future growth.
Time to impact?	The task is urgent, with current network decisions already being dictated by energy footprints. Bearing in mind the cycle from research to new telecom products, current research would impact within 5 years, but have a long-lasting impact in longer time periods.
Comparison with current solutions?	The continuing development of telecommunication equipment will lead to an improvement in energy efficiency - something that is essential if the kit is to meet limitations set by regulation and standards. However, solutions are rarely designed with an energy limitation constraint. Further, air conditioning is not entirely effective. This is amplified when dealing with the increasing equipment power dissipation, which is hampered by the limitations of air cooling.
What kind of research?	Research is needed into network design that minimises energy, especially in networks dominated by power-hungry IP routers. Photonics is of course very energy efficient and so optical solutions will be extremely desirable and often be lower power than alternative solutions. However, this development needs to go hand in hand with work on the components and subsystems. Finally, the entire heat management process will need a radical solution, and this includes looking at alternative cooling technologies, such as liquid cooling.
EU impact?	EU operators often work in buildings built many years ago, which were never designed for this level of traffic. Nevertheless, the requirements for CP's to become carbon neutral will only be met with ingenious research into increased efficiency.

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