Programmable Multi-Granular Optical Networks: Requirements and Architecture

Invited Paper

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Abstract—**This paper presents a programmable multi-granular optical cross connect (MG-OXC) and network architecture deployable in multi-service and multi-provider networks. The concept of programmable MG-OXC is introduced to provide a way of utilizing multiple switching/transport granularities to efficiently support the emerging traffic demands in both core and metro networks. For this reason, the supported bandwidth granularities include full lambdas, sub- and super-lambdas and multiple transport formats such as bursts, flows and packets. The programmability is envisaged by a software/hardware platform that simplifies network control, re-planning at the logical level and end-to-end service transparency, by translating the technology-specific information to technology independent services in an abstracted and logical manner.**

Keywords-component; multi-granular optical cross connects, programmable networks, optical burst switching

I. INTRODUCTION

As the Internet becomes ever more sophisticated, ubiquitous and powerful, a new generation of distributed network-centric applications emerges. This ranges from increasingly demanding services to end users (e.g. HDTV, gaming, SAN, etc.), to high-end distributed computing applications (cf. cloud computing). These applications exhibit a broad range of requirements in terms of (high to ultra-high) bandwidth as well as dynamicity and diversity, and hence increasingly complicate efficient end-to-end service delivery. Furthermore, many services, resources and customers can be dynamically added or removed, that were not envisaged during network design. Hence, the success and growth of the network-centric applications depends not only on networking infrastructure but also on the network services provided.

Thus it is vital to understand and redefine the role of networking, in order to implement one single high-performance network able to support applications having a diverse range of requirements. This network should provide different transport services, offering a flexible, scalable and cost-effective solution to service providers. Quality of service (QoS) parameters such as bandwidth, throughput, delay, jitter, packets loss, and possibly asymmetric point-to-multipoint connection identify the kind of network characteristics that may be required by these particular network services. In order to respond to a flexible and distributed environment, care should be taken to consider a flexible architectural and technological solution that is sustainable and can reflect the characteristics and requirements of emerging (dynamic) network-enabled applications.

Addressing these challenges, this paper introduces a flexible architectural solution, based on photonic technologies, that is sustainable and supports the characteristics and requirements of emerging (dynamic and diverse) network-enabled applications as well as service providers' needs. The architecture considers a multi-granular optical cross connect (MG-OXC). It combines multiple switching granularities (not only full lambdas, but also sub- and super-lambdas granularities to support multiple transport formats such as burst flows and packets) to efficiently support the aforementioned emerging traffic demands in both core and metro networks.

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In addition, the concept of *programmable* MG-OXC is introduced to provide a software/hardware platform that simplifies network control, re-planning (on a logical level, e.g. topology) and end-to-end service transparency by translating the technology-specific information to technology independent services on an abstracted and logical manner. This will enable flexible and efficient use of network resources. The novel and distinguishing key feature of this approach is the design of such an open programmable node, which will allow multi-service and multi-provider management of the switch, and the related interfacing with an enhanced control plane to support multi-granular services. The proposed solution will enable dynamic configuration and exploitation of switch resources and will make them controllable by any type of network service providers or even from end-users/applications.

The aim of this paper is to initially provide an overview of the related work and state-of-the-art technological solutions that can be used in multi-granular switching architectures and programmable networks. The main scope is the description of the proposed programmable MG-OXC and in turn overall network. In detail, the paper is organized as follows: Section II presents the related work and state-of-the-art on MG-OXCs and programmable node and networks. Section III describes the need and rationale for programmable multi-granular optical networks (MG-ONs). Section IV provides insight on the structure of the programmable MG-OXC architecture together with the main building blocks needed for its implementation. Finally Section V concludes the paper.

II. RELATED WORK AND STATE-OF-THE-ART

A. Multi-granular optical nodes and networks

Optical technology has been considered suitable to be employed and exploited not only for transport purposes, but also in the network nodes to perform switching functions directly in the optical domain, thus avoiding optical/electro/optical (OEO) conversions, which represent a typical bottleneck in high-speed networks. The design of optical switching nodes is a challenging task to obtain flexible architectures able to dynamically manage traffic flows at different time scale and traffic granularities. An MG-OXC is a switch that enables different transport techniques to cope with the different and evolving characteristics of application flows, according to the required QoS.

Various existing optical devices can be employed to design an optical MG-OXC such as Semiconductor Optical Amplifiers (SOAs), Micro-Electro-Mechanical-Systems (MEMS) and acousto-optical devices. These devices are already available and exhibit differences in switching time and cost. MEMS provide slow switching time, in the order of milliseconds, while SOAs provide fast switching in a few nanoseconds. On the other hand, MEMS are more scalable (1000×1000 devices are available) and cheaper, while SOAs devices do not scale well (currently 32×32 maximum size) and are much more expensive. A switch that employs different kinds of components or technologies is called hybrid. The idea is to exploit these differences to design a switch optimized in terms of resources employment, in relation to multi-granular application needs. The MG-ON node will concentrate on such a hybrid MG-OXC matrix.

Work has been recently developed on hybrid architectures, and has been reported in literature [1]. Devices for constructing optical switching fabrics have been characterized, considering aspects such as signal quality, scalability, blocking and physical performance [1]. Optical switching matrices and their associated scheduling algorithms within a node have been also widely studied [2,3] to achieve cost optimization and switch scalability [4]. Test-beds have been set up to demonstrate the feasibility of Optical Burst Switching (OBS) paradigm with a variety of switching devices [5, 6, 7, 8, 9]. Performance evaluation of hybrid optical switches has been carried out [10, 11, 12, 1] and the hybrid approach has been compared with the use of a single technology [13, 14]. Furthermore, an initial design analysis of architectures for MG-OXC has been undertaken [15], and it has been shown that the performance of hybrid architectures is little different from that of switches equipped with fast technology only, while the cost and scalability of the hybrid approach are superior. Dimensioning studies of OBS/OCS network exploiting MG-OXC have also been reported [16, 17].

Recently, a test-bed that implements an OBS multi-granular core node has been realized to demonstrate the feasibility of the concept [18]. Furthermore, an experiment has been performed which shows that such a multi-granular test-bed matches the requirements of service-oriented networks [19]. Also, broadcast-and-select data-plane multi-granular architectures have been designed to improve scalability and flexibility [20]. Yet, previous work focused purely on the design of the hybrid switch architectures and their ability to carry different granularities. So far, the architecture designs did not take into account their interfacing with the control plane and, even more important, the possibility to make the node 'open' and programmable in a flexible way. This paper mainly focuses on the latter unaddressed issues. In addition, careful analysis of how to map particular applications to the available switching capabilities still is a largely unaddressed area of research.

B. Programmable optical nodes and networks

The continual increase of computational power and the advent of programmable network technologies (e.g. specialized network processors and programmable devices - FPGAs) have changed the assumption of flexibility provided by the control systems applied at the intermediate network nodes (mainly electronic). The design principles of programmable networks were introduced to facilitate more flexible and scalable IT networked architectures. In this theme, services such as packet filters, firewalls, proxies, and congestion control or even QoS mechanisms were placed at intermediate electronic routers. However, such complex services have not been introduced in optical networks since the combination of ever increasing volume of traffic and complex packet level processing would heavily impact the complexity and cost of the nodes.

The constant increase of IP network traffic has driven network operators to deploy transport systems that accommodate higher Gbps rates per lambda interface. So, the existing WDM transport systems originally designed for 10 Gbps per lambda

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must either be rebuilt with new transport systems or upgraded to support transmission at higher bit rates (40 Gbps or even 100 Gbps per channel) and also support different transport technologies such as SONET/SDH, OTN and Ethernet. In most of the conventional transponder-based WDM networks, a service is directly coupled to a specific wavelength. So, the challenges amount to accommodating such diverse solutions, as well as to increasing the operational simplicity for service planning, engineering, deployment and growth. To this extent, network operators anticipate the deployment of additional capacity and support of new service types quickly and easily, with a minimum intervention. This should mainly be a matter of software-based network reconfiguration, which redefines the concept of programmable optical networking. Bandwidth virtualization has been proposed as one of the key elements of programmable optical networks. This allows a variety of service provisioning, stretching from sub-lambda to super-lambda data rates [21]. However, even if this approach brings more flexibility on transport resource utilization and in turn service provisioning, the use of electronic nodes for transit traffic maintains the high level of processing complexity and cost per bit.

III. RATIONALE FOR PROGRAMMABLE MULTI-GRANULAR OPTICAL NETWORKS

A. End user's application requirements

On distributed IT networks, a range of service types, resources and customers can be dynamically added or removed, including those, which were not envisaged during network design. Thus, fragile mechanisms that depend on the unique characteristics of specific computing and networking platforms are likely to have a negative rather than positive impact on the long-term efficiency of such an IT networked environment. The IT and network resource pools are heterogeneous and owned by several entities, the availability of resources can change at any time, and new types of resources are continuously added to the pool as older technology is removed. In order to respond to a flexible and distributed environment, care should be taken to consider a flexible architectural and technological solution that is sustainable and can reflect the characteristics and requirements of emerging (dynamic) network-enabled applications. This consideration should facilitate the provisioning of deterministic services and also provide a generalized and scalable solution beyond specific applications. A number of network-enabled application categories and their requirements are discussed below.

End-user applications mainly comprise information-based applications that represent end users. Such applications include web browsing, multimedia (e.g. video conferencing, video broadcasting and voice over IP), peer-to-peer file exchange, on-line gaming, distributed storage and message-based applications based on email and File Transfer Protocol (FTP). These represent both Internet users with everyday traffic patterns, and also non-strict network services. A number of these applications together with their service requirements were obtained from [22] and are shown in Table I.

High-end applications (e.g. Cloud, Grid, e-Science) that are characterized by the synergy between a distributed computing system and a high capacity and dynamically reconfigurable transport network:

- Distributed Supercomputing applications are distinguished by the scale of their resource requirements in terms of peak computing speed, memory size, and communication volume, as well as tightness of the coupling between the computational modules [23].
- High-throughput Computing (HTC) applications [24] are driven by aggregate, rather than peak performance requirements. Throughput-oriented users measure the power of the system by the amount of work it performs in a fixed amount of time [25].
- Distributed real-time applications [26] often require many capabilities such as distributed system components (e.g. instruments and imaging systems), data stream management and high speed networks._Real-time systems exhibit both high data rates and the need for real-time cataloguing.
- Data-intensive applications [26] also often have demanding computational component requirements. Application development is driven by the need to process and analyze information, rather than the need to simulate a physical process.
- Tele-immersion applications [26] require bandwidth-complete model terms that relate bandwidth requirements to the size and nature of distributed world models.
- Collaborative applications require delivery of many channels of real-time streaming audio and video into an audiovisual display environment, scalable interconnection of many users and worlds, close coupling of the virtual

TABLE I. END –USERS' APPLICATION REQUIREMENTS.

Type of Service	**Bandwidth (Mbps)**				**Max delay**	**Max jitter**	**Packet loss**
	Peak down	*Peak up*	*Mean down*	*Mean up*			
Video BroadCast (SDTV mpeg2)	6	0	6	0	<2s	<40ms	<3E-3
Video BroadCast (HDTV mpeg2)	20	0	20	0	<2s	<40ms	<3E-3
VoIP	0.1	0.1	0.1	0.1	<70ms	<20ms	<3E-3
Gaming	0.25	0.25	0.20	0.20	<50ms	<10ms	<5E-2
Video Conference	3	3	2.2	2.2	<100ms	<10ms	<3E-3
SAN (Back-up/Restore)	400	400	324	324	<500ms	<50ms	<5E-2
SAN (Storage on Demand)	1000	1000	810	810	<10ms	<1ms	<5E-3

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worlds to distributed networks of large-scale simulations and databases, and real-time interactions.

B. Rationale of Programmable MG-ON.

Programmable MG-ON aims to answer the aforementioned applications' needs for flexible networks with MG-OXC architectures. Specific MG-OXC architectures [18] have been proposed to dynamically switch optical packets, bursts, wavelengths and wavebands together in one optical switching fabric. Each MG-OXC can incorporate a range of switch device technologies, each with its own characteristics such as switching times, which are optimized to particular transport services.

Because of the resource-intensive nature of many of the applications described above, dedicated networks are currently regarded as a possible solution. However they each do not exhibit sufficient flexibility to efficiently satisfy the requirements of every foreseeable application type. Also, it is not economically viable to deploy, operate and manage several such dedicated networks; clearly a single network would be much more cost-effective. Furthermore, when they fulfill service requests, dedicated networks generally do not do so independently of technology, and do not provide a data transport service that is transparent to application software. Hence it is vital to understand and redefine the role of networking, in order to implement one high-performance network, which can support applications having a diverse range of requirements, which will also offer service providers a flexible, scalable and cost-effective solution.

Requirements differ from application to application in terms of granularity of traffic flows and traffic characteristics such as data transaction bandwidth, acceptable delay and packet loss, as well as connection stretch (for example, access-metro, access-metro-core, access-metro-core-metro-access) and number of end-points (point-to-point, point-to-multipoint, multipoint-to-point or multipoint-to-multipoint). However, it is evident that the success and growth of such network-enabled applications depends not only on networking infrastructure but in turn also on the services provided. Parameters such as bandwidth, throughput, priority, latency, loss and the need for a point-to-multipoint connection identify many of the principal network characteristics that are required by a particular network service [27].

In such distributed environments with diverse network-driven applications, MG-ON based upon MG-OXCs are best suited to fulfill many of those requirements. Utilization of WDM, tunable technologies, MG-OXC and multi-granular transport paradigms (packets/bursts) can provide granular characteristics to distinct applications. Characteristics such as bandwidth, wavelength, or even sub-wavelength granularity combined with switching devices, ports and equipment can be adapted and controlled in order to provide deterministic services. A clear understanding of the performance and applicability of MG-ON to the future Internet is provided by Table II, which portrays different optical transport technologies against numerous network performance aspects. Burst mode transport paradigms (Optical Burst Switching – OBS, possibly over circuit-switched tunnels as in Burst-over-Circuit Switching – BoCS) have the advantages of both Optical Packet Switching (OPS) and Optical Circuit Switching (OCS), and also seek to overcome their weaknesses.

This comparative table shows that an MG-ON technology based upon MG-OXCs can create a platform to support a broad range of applications and traffic demands, because it can employ the favorable functionalities of both OCS and OBS. OBS networks have the flexibility to select circuit switching (lightpath), flow switching (persistent connection) or per-hop switching (single burst) services, depending on the connection set-up message. OBS is foreseen as a viable solution for future optical networks because it offers increased bandwidth utilization over circuit switching and is easier to deploy than packet switching [28]. Various performance analyses [29,30] show that OBS can better handle the statistical multiplexing properties of IP traffic, reducing the required number of wavelength channels over a circuit switched solution. However, this is true only when variable length bursts are considered, of both long duration (tens or even hundreds of milliseconds) and relatively small duration (several microseconds).

Although such a multi-granular solution clearly has compelling advantages, current optical cross-connects (OXCs) operate only at the granularity of a single wavelength, or in some cases at waveband granularity. They hence do not provide the flexibility of switching at sub-wavelength granularity through optical packet switching (OPS) and optical burst switching (OBS). Furthermore, these current OXCs are closed units that can only execute a restricted set of vendor software, which is dedicated to providing a relatively small range of very specific pre-defined network services. Because

TABLE II. COMPARISON OF DIFFERENT OPTICAL TRANSPORT AND SWITCHING TECHNOLOGIES.

Optical Transport Paradigm		**Band-width Utiliza-tion**	**Latency (setup)**	**Switching speed**	**Implementa tion**	**Traffic adaptability**	**Loss**	**Granularity**
OCS		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
BoCS		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
OBS	**Two-way**	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	One-way	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
OPS		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

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this clearly limits the range of application requirements that can be satisfied, a key feature of the proposed architectural solution is the introduction of sophisticated software, which will enable MG-OXCs to be fully programmable and configurable by the application software. This will facilitate application-aware networking, where the appropriate network service granularities are offered through the appropriate protocol adaptation layer, tailored to each specific application request. The proposed network architecture consists of MG-OXCs driven by sophisticated control software allowing abstraction and resource virtualization.

IV. PROGRAMMABLE MULTI-GRANULAR NODE AND NETWORK ARCHITECTURE

Each node in the proposed network will be a MG-OXC, which can be configured to provide an adequate level of QoS to the applications, by exploiting the different switching granularities simultaneously, based upon resource availability. Such a MG-OXC allows the network to support different transport techniques, with different latency, loss and end-to-end delay characteristics, and to apply them as appropriate for various applications needs. As a result the network infrastructure will be partitioned into virtual networks, through abstraction of network resources, thus allowing different providers to share these resources and hence turning into a multi-service, multi-provider network concept.

The edge and core nodes in the MG-ON architecture will efficiently aggregate traffic and manage their resources as appropriate in order to perform data forwarding: this is the task of a *MG transport module*. This, as well as the MG-OXC switching matrix (denoted as a *MG switching module*) must be managed by appropriate control and scheduling algorithms to dynamically configure switching resources and support network services. Network features far beyond those provided by node re-configuration in today's networks will be obtained, including resource virtualization. One of the key features is the programmability of the node: description, allocation and re-programming of transport and switching elements will be possible. Abstraction mechanisms will be used to achieve also higher level customization of the node's operation.

Fig. 1depicts the proposed node architecture, which consists of three layers, and a GMPLS control plane on top of them. The bottom layer contains the *Multi Granular (MG) transport and switching modules*. These are the actual electronic, opto-electronic and optical devices responsible for shaping and mapping the incoming data to Multi-Granular transport formats as well as switching the MG bypass traffic. The main objectives that will be addressed in this layer of the MG-OXC will consist of:

- The definition and implementation of efficient algorithms to aggregate traffic and find the appropriate transport service to match QoS requirements (such as latency and loss).
- The design of MG-OXC architectures to support a broad range of transport services, with switching capabilities ranging from sub- to super-wavelength (waveband) levels. Clearly, this will include appropriate interfaces between transport and switching modules.
- Definition and development of a programmable MG transport element to allow remote dynamic re-configuration in order to customize existing transport mapping and aggregation algorithms or introduce new ones.

The middle layer of the proposed MG-OXC is entitled "*technology-specific control module*", and has three main roles:

- The first role refers to overall control of the lower layer. This is required in order to coordinate all MG-OXC resources under a single entity. This coordination consists of description, allocation/ configuration and programming of all transport and switching modules.
- The subsequent role tackles the issue of scheduling algorithms required to manage resources and contention resolution in MG-OXC, which arises over different time scales and with QoS support.
- The last role engages a higher level of resource programmability in order to:
    - Describe, allocate and re-program the MG switching elements to create different cross-connect architectures.
    - Describe, allocate and re-program the MG transport elements to provide new transport formats.

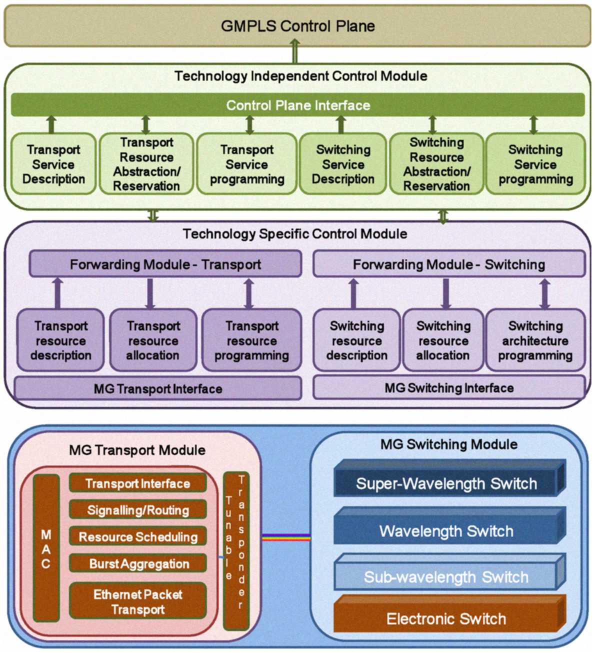

Figure 1. Programmable MG-OXC architecture.

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The upper MG-OXC layer is the *technology-independent control module*, which is proposed in order to simplify the interaction with network service providers. This enables sharing of MG-OXC resources, accelerating the creation of new services and in turn driving innovation in both network and non-network sectors. The proposed programmable MG-OXCs can be used to allow even non-network service providers (such as those engaged in video broadcasting, or providing virtual reality online gaming) to provide network services, and open up the network provisioning market. To realize such innovation this control module requires the following functionalities:

- MG-OXC abstraction algorithms for node/bandwidth virtualization and segmentation.
- Reservation of technology-independent network transport and switching services through partial hardware-embedding of light signaling protocols.
- Definition and development of an interface with the technology-specific control module.
- Definition and development of a northbound interface to interoperate with higher layers (such as the GMPLS control plane).
- Extensibility and scalability of hardware-accelerated electronic modules to be implemented within each MG-OXC.

Interconnecting multiple MG-OXCs with the aforementioned architecture, a MG-ON can be realized. This facilitates deployment of a single network, potentially with sufficient capacity and flexibility to satisfy the requirements of multiple foreseeable application types (rather than different networks, each tailored to only a subset of these applications). The MG-ON single metro-core solution limits the opaque interconnection of access-metro, and metro-core to a single element – the transport module within each MG-OXC – that shapes incoming traffic. In addition, the proposed MG-ON is based on both programmable MG-OXCs and a dynamic MG-ON enabled GMPLS control plane that can provide end-to-end service delivery, independent of the underlying technology. This allows for creation and provisioning of data transport services, and provides horizontal transparency across access-metro-core networks as well as being vertical to both the service provider's solution and, in turn, to the application software. The use of a single transport network solution also seeks to minimize the overall cost of transport network elements. Possible use cases (shown in Fig. 2) can consider use of different transport formats (e.g. burst trains, Ethernet packets) over connection-oriented or connectionless lightpaths using super-wavelength, wavelength and sub-wavelength switching granularities. The selection and use of the MG network service approach will be influenced on one hand by applications/users with different traffic profiles, QoS requirements and lightpath stretch and on the other by the intrinsic needs of network service providers.

V. CONCLUSIONS

The concept of programmable MG-OXCs and the main functionalities required at the node but also at the network level have been presented. The proposed modular and scalable architecture of MG-OXC can be programmed to provide in-operation dynamic software/hardware node and network re-planning. This seeks to ensure that network dynamically responds to new traffic demands and application requirements and tune existing services or create new ones that meet the needs of subscribers and operators. This architecture decouples the technology-specific transport and switch elements from technology-independent network service parameters, which can

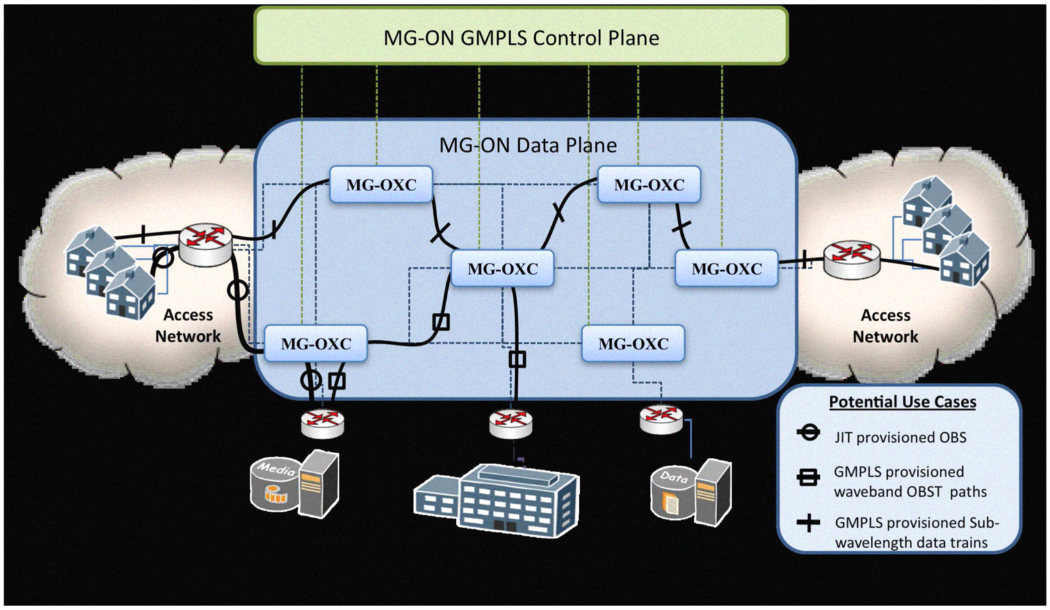

Figure 2. Programmable MG-ON architecture.

be used by the control plane to provide more efficient end-to-end services. However, MG-OXC programmability would allow infrastructure providers to share their resources among multiple service providers either on technology-independent layer or technology-specific layer. In the second case service providers can also have access to software/hardware programmable elements to tune the resources control in order to introduce their own scheduling/forwarding/buffering solutions.

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