Energy Efficiency in Optical Networks

(*invited paper*)

Raffaele Bolla[1], Roberto Bruschi[1], Pasquale Donadio[2], Giorgio Parladori[2]

1 – CNIT, Research Unit of the University of Genoa
Genoa, Italy
{name.surname}@cnit.it

2 – Alcatel-Lucent Italia
Milan, Italy
{name.surname}@alcatel-lucent.com

Abstract—**This paper proposes a new framework, specifically designed for introducing and suitably managing/using green metrics in ASON/GMPLS Optical Transport Networks (OTNs). The core element of such a framework is the Green Abstraction Layer (GAL), a standard interface proposed by the ECONET project, which has been specifically designed to give a simplified a common view of power management primitives available in next-generation green network equipment. The Green Abstraction Layer allows to extract available power management settings, and to set the desired configuration into a device, hiding heterogeneous and complex details of device internal physical architecture of nodes.**

Keywords-green networking; optical networks; abstraction layer.

I. Introduction

Network energy efficiency has become an aspect of paramount importance for Telco operators and Internet Service Providers (ISPs) across all network segments (wired and wireless), owing to the increasing power consumption exhibited over the years [1] and to the increasing cost of energy. Estimates of public organizations [2] provide alarming figures in the “Business As Usual” case; for the sole European Telcos, the estimated energy requirement in 2020 would result into an increase of over 67% in a decade.

Among the main reasons for such high power consumption are the increasing user traffic and router capacities, which are not compensated by a corresponding increase in silicon energy efficiency. Moreover, the vast majority of currently deployed network links and devices are designed to operate (and, consequently, to consume power) constantly at their maximum capacity, irrespectively of the traffic load, even though their average utilization lies far below the maximum [1,3]. These observations have suggested the possibility of adapting network energy requirements to the actual traffic profiles [4-5]. Just similarly to general purpose computing systems, such possibility can be realized by including Power Management Primitives (PMPs) into the silicon platforms of networking devices, where energy absorption physically happens.

Contemporary backbone data networks are mainly using distributed IP routing so as to move packets from source to destination. Moreover, the transport network is typically used for providing static point-to-point high capacity connectivity among IP routers. From the energy consumption point of view, this backbone architecture is far from being optimal since it is heavily based on power hungry electronic routers. Furthermore, as the Internet continues to grow, it requires network elements with larger capacity, higher transmission rate and faster processing speed. With the exponential traffic increase in IP traffic, remaining at lower layers when possible is advantageous for operators wanting to keep their energy bills under control. As a result, the most eco-efficient architecture is a multilayer one that can automatically direct traffic to the lowest level of switching required according to bandwidth, network availability and service requirements. A network design approach that is currently promoted, especially by transport equipment vendors, in order to address contemporary backbone data networks power consumption inefficiency, is called “router by-pass” or “router off-load”. The main idea of this approach is that transport equipment’s intelligence is enhanced so as to be able to dynamically establish high capacity circuits minimizing the number of IP routers.

In this respect, OTNs constitute the best candidate since they can exploit the enormous bandwidth of optical technologies and the flexibility for establishment of end-to-end optical circuits among various nodes. OTNs also provide efficient sub-wavelength bandwidth management capabilities. Multiple transport options are available for individual management of traffic relations generated in the IP routing layer. OTN’s features provide a transport foundation for IP traffic relations on which router ports and even sub-ports can be mapped to the most optimal transport entity: a wavelength, a fixed-rate virtual container (Optical Data Unit, ODU) or a variable-rate virtual container (ODUflex). By augmenting such architectures with GMPLS (Generalized Multi-Protocol Label Switching) technology that enables control plane integration, operators can automate the selection of the most power-efficient layer. Regarding the network control plane, it may also be utilized efficiently for reducing energy consumption. An ASON (Automatic Switched Optical Network)/GMPLS optical control plane simplifies network operations with the goal of creating a ‘self-running’ network in which ‘the network is the database’. With ASON/GMPLS, the network has the intelligence to dynamically choose the most power-efficient layer for transport. For instance, during the night when networks carry very low traffic volumes, it will be possible putting some energy-hungry silicon-based devices/elements into standby modes, or decreasing their working capacities by redirecting the traffic at the all-optical level. By enabling resilient, automated and power-efficient networks, GMPLS brings a number of CAPEX and OPEX advantages in addition to eco-benefits.

This paper tries to foster these concepts by proposing a new framework, specifically designed for introducing and suitably

978-1-4673-1391-9/12/$31.00 ©2012 IEEE

managing/using green metrics in ASON/GMPLS OTNs. The core element of such a framework is the GAL, a standard interface proposed by the ECONET project, which has been specifically designed to give a simplified a common view of PMPs (i.e., standby and power scaling) available in next-generation green network equipment. The GAL allows to extract available PMP settings, and to set the desired configuration into a device, hiding heterogeneous and complex details of device internal physical architecture. For this reason, the GAL can be though as the key tool for binding power management, performed at the device HW, with the ASON/GMPLS control plane, acting at various levels of logical network resources.

The paper is organized as follows. Sect. II introduces a survey on current OTN technologies. Sect. III focuses on the use of PMPs in OTNs. The GAL is introduced sect. IV, and sect. V discusses how to use it in an ASON/GMPLS environment. Finally the conclusions are drawn in sect. VI.

II. The State of the Art in Optical Transport Networks

With the recent technology evolution in the OTN domain, the WDM transport layer migrated from simple point-to-point transmission links into elaborate network architectures providing similar functionality to the electronic SONET/SDH layer, with improved features, higher manageability and lower complexity and cost [6,7]. Integrated WDM networks performing switching and routing are deployed in order to economically support the required functionalities [8]. In such network scenarios, high capacity optical paths are set in the transport layer forming connections between discrete points of the network topology, utilizing intelligent dynamic network elements. These can be identified to be reconfigurable Optical Add/Drop Multiplexers (OADMs) and Optical Cross-Connect (OXC) nodes performing traffic engineering and management of the optical bandwidth [9-11]. Most specifically they support handling of the incoming signals at the appropriate granularity level to enable efficient routing of the traffic demands satisfying the service level requirements including network survivability and security and accommodate network expansion, traffic growth and churn. Taking into consideration the discussion above, it is straight forward to classify the optical network technologies into optical transmission, switching and control technologies depending on their role and functionality in the network. A relevant taxonomy diagram is illustrated in Figure 1. The following sub-sections will concentrate on describing the relevant technologies and identifying alternative options available through the relevant state-of-the-art.

A. Optical networks core transport and switching architectures

Apart from the application to the optical transport level, OTN standards are expanding to switching and aggregation applications. The aggregation/grooming switches that the operators have deployed in major locations of metro and long-haul networks are going to be upgraded to OTN switches that operate at the OTU layer. This will imply the transparency of the network to underlying protocols, the guarantees of the end-to-end optical performance and the efficient resource utilization coming from the efficient traffic grooming. IP over DWDM has been proposed as an alternative to SONET/SDH for IP packet transmission over optical fiber networks.

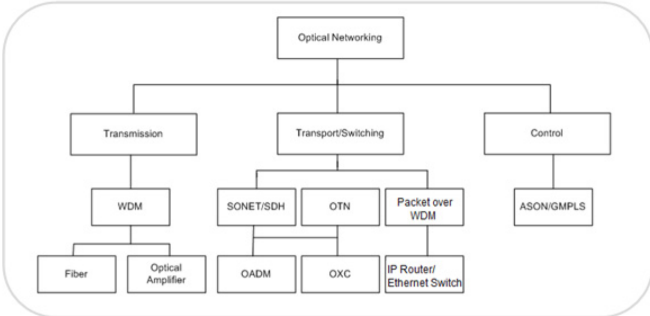

Figure 1. Optical Network Taxonomy.

From a high-level perspective, core nodes are optical-electrical-optical based. This means that all optical traffic is converted to the electric domain and processed by node, weather the traffic is terminated at this node or not. The all-optical transport layer is more cost efficient (simplification of the network layers) and maintains high data rates. Benefits of this solution are related to faster path provisioning. However, several disadvantages arise from the fact that router ports are expensive compared to switch or transmission cost. In addition, inherent scalability issues associated with the IP router technology as well as the very high energy consumption levels associated with this type of equipment when compared to their optical technology counterparts, may introduce serious drawbacks regarding their suitability for a sustainable Future Internet solution.

10 Gigabit Ethernet is an extension of the same standard to 1 Gb/s. Gigabit over fiber is becoming a popular choice in metro networks to interconnect multiple enterprise networks. The 10 Gb/s standard is begin developed with the internet of enable long-haul interconnections, with the data rate begin aligned to the OC-192 rates for better compatibility with wide area transport.

B. Optical Switching Equipment

As WDM is evolving into infrastructures that perform a variety of functions beyond simple p2p transmission including management of the available bandwidth the required optical switching equipment are optical network elements that handle/manage the optical bandwidth. This bandwidth management is performed at the appropriate granularity level to enable routing of the traffic demands with the aim to support the corresponding QoS. These network elements can be identified to be OADM and OXC nodes that can operate at different levels of optical bandwidth granularity. This type of nodes offer traffic engineering capabilities and functionalities such as point-and-click provisioning, bandwidth on demand, resilience and other advanced features depending on their specific architecture and design details. These network elements can be identified to be optical switching nodes that functionally correspond to a generic architecture similar to the one illustrated in Figure 2. These elements include the functionality of OXC and OADM nodes together with the payload assembling/disassembling (PAD) and any wavelength conversion capability that maybe available in these nodes.

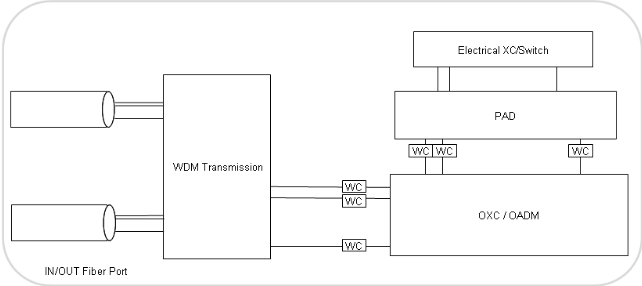

Figure 2. Functions of an Optical Cross Connect Node [12]

C. Transparent and Opaque Networks

Transparency in optical networking refers to the ability to modulate and transmit any kind of payload on the optical channel, independent of its bit-rate and format (framing, line-coding, power level, etc.). Transparency implies that a specific optical path (lightpath) is assigned between each origin and destination node pair without any Optical-Electronic-Optical (OEO) conversion at any intermediate node. Transparent optical networks generally provide reduced operational costs associated with their inherent energy efficiency, but suffer by the physical layer impairments associated with the optical transmission of the data channels. In addition, they do not inherently support wavelength conversion capability and signal monitoring functions. However, wavelength conversion capabilities can be introduced through the use of transparent optical wavelength converters [12]. Opaque networks are on the other hand based on nodes equipped with OEO technologies. These networks commonly inherently support wavelength conversion functionality and signal monitoring capabilities. However, they require higher energy consumption levels for their operation and occupy larger footprint compared to their transparent counterpart. A practical solution that is commonly deployed with the aim to overcome the limitations of both transparent and opaque optical networks is translucent optical networks.

1) Transparent Optical Nodes

In case of transparent (all-optical) OXCs, the incoming wavelength channels are routed through an optical switch fabric without the requirement of optoelectronic conversions. The switching granularity may vary and support switching at the fiber, the wavelength band or the wavelength channel level. The main characteristics of photonic switches are related to the lack of optical conversion, granularity, reliability, scalability, switching speed and bit-rate and protocol transparency.

OADM technology provides add/drop capability of any data rate wavelengths and delivers great flexibility and cost savings on optical transport platforms. Reconfigurable OADMs (ROADMs) automate and simplify optical network planning and configuration be enabling add, drop and express functionality for any of the wavelengths on a fiber in any combination. They also allow traffic to pass through a network node transparently, without the need for OEO conversion. The planning process in DWDM networks is simplified by the ROADMs by allowing the addition, removal or modification of one or more optical channels automatically, minimizing user intervention.

2) Opaque Optical Nodes

Opaque OXCs include conversion of the optical signal to electrical and after some processing conversion back to optical again and can either be based on electrical switching technology or on optical switch fabrics. In both cases there is a requirement for optoelectronic conversions equal to the number of wavelength channels supported by the OXC. Opaque OXCs depend on whether they utilize optical or electrical switch fabrics can offer different features. In OXCs using electrical switching, sub-wavelength switching granularities can be supported providing grooming capabilities for more efficient bandwidth utilization. Opaque OXCs utilizing electrical switch fabrics also offer inherent regeneration, wavelength conversion and bit-level monitoring. Alternatively opaque OXCs employing optical switch fabrics normally support switching at the wavelength level without any grooming capabilities, but offer inherent, regeneration, wavelength conversion and bit-level monitoring.

3) Multi-granularity Optical Nodes

Multi-granularity switches have been proposed and extensively discussed in the literature [13-15] as they provide increased flexibility solutions. The main benefit provided by such an approach is the reduced loss, improved cascadability and reduced cost for the traffic handled at the lower granularity levels e.g. fiber and wavelength bands and more efficient bandwidth utilization for the traffic handled at sub-wavelength i.e. higher granularity levels. Higher levels of granularity are suitable to also handle the bursty nature of the traffic supported by today and future multiservice networks. Multi-granularity switching nodes have a special impact in the context of optical network virtualization, as they can facilitate virtualization at different granularity levels thus improving the efficiency with which the physical network resources can be utilized.

D. Network Control Plane (NCP)

The NCP enables the evolution from centralized to distributed control of access, metro, regional and long-haul networks. It operates over multiple vendor and operator environments and technologies like IP, Ethernet and optical networks and in a simplified view it has the role to dynamically setup connections across an optical transport network. The main benefits of an NCP are: (*i*) Distributed and reactive traffic engineering, allowing network resources to be dynamically allocated to connections; (*ii*) Usage of specific control plane protocols rather than generalized network management protocols; (*iii*) Distributed and reactive restoration upon a network failure, taking into account current state of the transport network; and (*iv*) Reusability of control plane protocols to handle different transport technologies under a common control framework.

1) NCP reference architectures: ASON and GMPLS

The ASON and the GMPLS are the two reference architectures for the implementation of the NCP. ITU-T ASON provides an architecture description for a control plane that operates over a transport network and supports functionalities like fast connection establishment and restoration for both permanent and soft permanent connections. IETF GMPLS originates from the MPLS protocols suite, whose main goal was to bring the speed of layer 2 switching to layer 3 and solve different complexity and scalability issues. Main features of MPLS were label swapping, separation of forwarding and control plane, forwarding hierarchy via label stacking, constraint-based routing, facilitation of virtual private networks, provision of class of service and elimination of multiple layers. It provides functionalities for resource discovery for links, nodes, topology and services, flow-through service provisioning, end-to-end connection routing for optimal resource utilization and service rerouting and restoration for protection against network failures.

III. Power Management in OTN Equipment

The first step towards a high bit-rate core network was the creation of electro-optical networks. In these kinds of networks, although the signal travelling through them was optical, all the processing in both ends of the connection and in the intermediate nodes was done in the electric domain. That is why they are also named opaque networks, that is, because the signal does not remain all the way from an end to the other in the optical domain; an OEO conversion must be done at some points to ensure a correct routing and Quality of Service (QoS). However, despite the improvements introduced by opaque networks, the limitations of the electrical processing of the signal was an important bottleneck for achieving a low-power/high bit-rate core network, so that the next step was migrating the backbone towards AONs, where the routing and the processing was done in the optical domain. ASON/ASTN is mainly the architecture used by these kinds of networks in conjunction with generalized multi-protocol label switching (GMPLS) as the technology used by the control plane.

The GMPLS framework is considered to be the emerging control plane solution for future optical networks. The main functionality that the GMPLS control plane offers in optical networks is the dynamic establishment and teardown of end-to-end optical connectivity. GMPLS currently does not include any mechanism to take into account energy consumption parameters when identifying end-to-end paths or disseminating the status of network elements with respect to their power consumption. Actually, the standard operates only in the direction to define an energy-aware control plane enabled by energy-aware routing algorithms and signaling as well as by specific energy optimization mechanisms. What is missing is the connection between the network control plane and the OTN equipment that takes in account of the application layer requirements and translates it in optical network resources with the objective to minimize the overall energy consumption while providing the QoS requested by the application. What we need is the definition of a standardized glue technology enabling the network control plane and the OTN equipment integration. For this purpose, the ECONET consortium proposes a novel standard interface, named GAL.

IV. The Green Abstraction Layer

Power-managed silicon devices need control loops able to dynamically tune hardware capabilities to provide the required QoS to incoming traffic with the minimal power consumption. It is also worth noting that PMPs are features locally available in network nodes, and their efficiency may heavily depend on the specific implementation and low-level details of the hardware of devices; the latter may be quite heterogeneous, even when considering equipment of the same market segment.

Starting from these considerations, the ECONET consortium is going to define and develop novel standard interface, the GAL [16]. The goal of the GAL is providing: (*i*) a common and simple way for representing power management capabilities available in heterogeneous data plane hardware; (*ii*) a framework for information exchange between power-managed data plane entities and control processes; (*iii*) a reference control chain allowing a consistent hierarchical organization of multiple local and network-wide control loops, namely local control policies (LCP) and NCP.

As such, the target of the GAL is to define a complete control interface that will allow managing the trade-off between power and network performance at the system level. In other words, the GAL is meant to make control loops able to acquire information on which power management settings are available at network data-plane and on their potential effect in terms of consumption and network performance metrics, in order to choose the most suitable configuration. Similarly to other standards in the same field [17] [18], among others, these types of information are formalized through the concepts of "energy-aware" states. However, in the present standards, the definition of power-aware states is rather coarse: both EMAN and ACPI provide pre-defined, non-extensible state sets. Furthermore, the power state description and characterization that existing standards provide is clearly insufficient for any remote control decision (e.g., lack of performance tradeoff indications in power state descriptions).

A. Main issues in the GAL design

The main problem in interfacing NCP (e.g., ASON or GMPLS) and the PMP of physical entities mainly relays on the fact that the largest part of network control protocols generally work on the top of logical resources, often losing the details on how they can be mapped on internal HW components, where power consumption and management happen. Thus, NCPs may drive power configurations of network device only by means of such logical resources. The GAL must consequently expose towards NCPs a number of "hooks," one for each logical resource, and abstracting/aggregating there the power settings available at the physical layers. Moreover, logical resources often provide a simple graph-like representation of the network and, then, of the node. No information on if two logical resources are set up in a same physical link, or in a same line-card, are generally made available. However, in the power management perspective, this kind of information can make the difference, since, for instance, a physical subcomponent can enter into standby mode (and then potentially save a huge amount of energy) if only if all its logical resources are turned into sleeping states [19]. It is worth noting that a logical link has no direct power management capabilities, given its logical and not physical nature. On the other side, power management operations executed at logical resource level may involve a number of physical elements. For instance, when a logical link is put into standby mode, the status of the link's physical layer chip can be changed, and the capacity of silicon circuits processing packets coming from that link decreased. To perform this kind of operations, the GAL must expose a number of “hooks” to the network control protocols, one for each logical resource. As said before, these hooks could be realized by adding a further GAL layer just above the highest level LCP of the HW tree (the one working at device level). The highest-level LCP must be in charge of exposing all the logical resources of the devices, whose number and types are dynamic and depend on the device configuration, to the NCPs.

At lower level, logical resources may be mapped in a number of physical elements. The way for performing this logical/physical mapping is substantially device-dependent, given the high heterogeneity of device internal architectures. For this reason, the ECONET consortium believes that delegating such aspects to LCPs, instead of integrating them inside the GAL, can provide an enough flexible and scalable solution. In other words, the role of LCPs is to interpret higher level requests and map them into the device HW, orchestrating the configuration of multiple sub-elements. At intermediate levels, the GAL interconnects a number of LCPs, each one governing the power management configuration of various device modules (from chassis to single line-cards) and orchestrating the behavior of underlying sub-components. At the bottom level, the GAL allows to configure single HW components (like ASICs, network processors, chips, etc.). To this purpose the GAL provides two interfaces: (*i*) the Green Standard Interface (GSI), thought to provide a standard and common representation of the PMP in terms of functionalities and capabilities; and (*ii*) the Convergence Layer, which is adopted at the bottom layer in order to map the high-level standard information/commands into HW-specific actions to be performed on heterogeneous physical platforms.

B. *Anatomy of the GAL*

The GAL framework (Figure 3) is a multi-layer hierarchical interface that allows the intercommunication among multiple local and network-wide control planes and the data-plane hardware. The different layers are thought to represent various abstraction levels of a power managed device. At the top of the hierarchy the GAL connects NCP processes, which work on logical resources of the device (Figure 4).

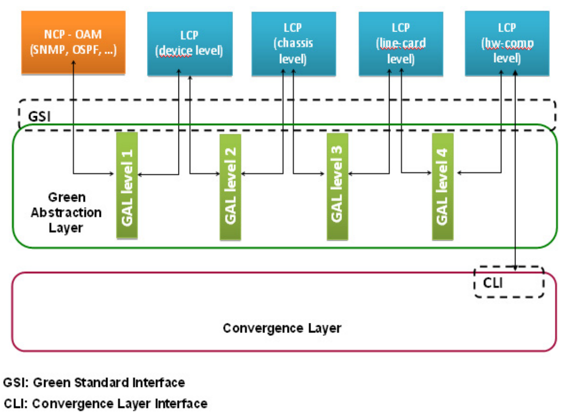

Figure 3. Green Standard Interfaces in the ECONET GAL architecture

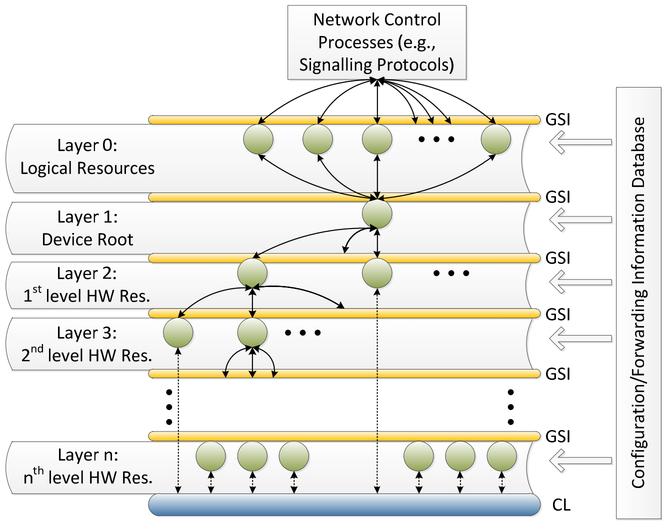

Figure 4. The GSI hierarchy, the circles represent LCPs working at various levels.

The GSI is the real core element of the GAL, and it is in charge to provide the command set necessary to setup the power management and monitoring of a wide set of energy-aware resources and network devices. In other words, the GSI is used for the access to resources and their power characteristics discovery, the autonomic provisioning and manual configuration of resources, the monitoring and the decommissioning of energy-aware physical resources. The main functionalities offered by the GSI are the following: *Discovery*: It is used to retrieve information about: (*i*) the current power state set in the entity; (*ii*) available power states and other descriptive information of the entity; (*iii*) measurement/monitoring points for reading power-related information; (*iv*) list of individually manageable components within the entity and their relation (both logical and physical); *Provisioning*: Allows the configuration of a power state into an entity; *Release*: Allows the energy-consumption release of already configured physical devices. After release, the device should exhibit its default configuration; *Monitoring*: Permits to monitors relevant parameters (state, power consumption etc.) of the physical device; *Commit*: to deploy the current configuration.

V. MERGING THE OTN NCP AND THE GAL

The actual tendency is to progress towards a two layer optical network all-optical DWDM transport network and an iP/Encapsulation Frame with GMPLS as the control plane. These networks, defined in ITU -G.872, have a control plane that directly configures the different transport plane resources. The ASON architecture fits well in these specifications. Although ASON aimed at deploying fully transparent OTNs, the presence of degradations on the physical layer of the network may prevent the transparency to be achieved completely. The main reason is that, despite the automatic resource allocation that ASON can offer, it is only based on topological and traffic parameters and does not take into account the actual physical transmission in such connections. Here, we propose an innovative architecture where the GMPLS is extended to the energy-aware OTN equipment providing interface functionalities and protocols between the application and the network infrastructure. To enhance the connection between the GMPLS control plane and the GAL we introduce the Path Computation Element architecture, which will be embedded in each energy-aware device or connected externally to it (distributed), or provided as centralized service. The figure 5 shows a possible integration of the GMPLS control plane and the GAL using the path computation element architecture. The PCE architecture introduces a special computational entity that will cooperate with similar entities to compute the best possible path through multiple domains. A PCE is a node that has special path computation ability and receives path computation requests from entities known as path computation clients. The PCE holds limited routing information from other domains, allowing it to possibly compute better and shorter inter-domain paths than those obtained using the traditional per-domain approach. Among other purposes, PCEs are also being advocated for CPU-intensive computations, minimal-cost-based TE-LSP placement, backup path computations, and bandwidth protection. Along with the process of identifying the requirements and development of the architecture accordingly, a plethora of work is underway at the PCE WG on the new communication protocols that will make this architecture work. This includes the development of new inter- PCE communication protocols and introducing extensions to existing underlying routing protocols. RFC 4655 specifies a PCE-based architecture. RFC 4657 covers PCE communication protocol generic requirements, and RFC 4674 discusses the requirements for PCE discovery.

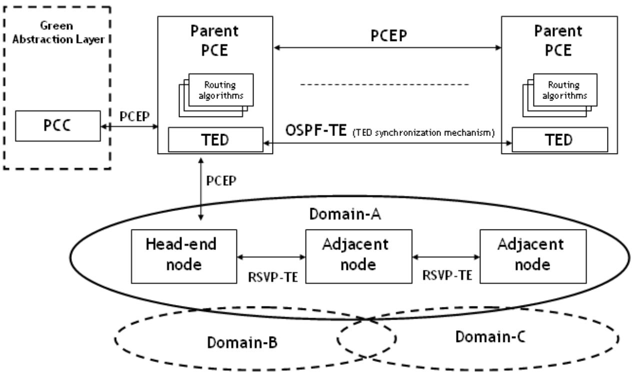

Figure 5. Green Abstraction Layer and GMPLS/PCE architecture integration.

VI. CONCLUSIONS

This paper proposed a new framework, specifically designed for introducing and suitably managing/using green metrics in ASON/GMPLS OTNs. The core element of such a framework is the Green Abstraction Layer (GAL), a standard interface proposed by the ECONET project, which has been specifically designed to give a simplified a common view of PMPs (i.e., standby and power scaling) available in next-generation green network equipment. The GAL allows to extract available PMP settings, and to set the desired configuration into a device, hiding heterogeneous and complex details of device internal physical architecture. For this reason, the GAL has been used as means for binding power management, performed at the device HW, with the ASON/GMPLS control plane.

ACKNOWLEDGMENT

This work is supported by the ECONET project, funded by the European Commission under FP7, G. A. no. 258454.

REFERENCES

[1] Bolla R., Bruschi R., Carrega A., Davoli F., Suino D., Vassilakis C., Zafeiropoulos A., “Cutting the energy bills of Internet Service Providers and telecoms through power management: An impact analysis,” Computer Networks, vol. 56, no. 10, pp. 2320-2342, July 2012.

[2] GeSI, “SMART 2020: Enabling the Low Carbon Economy in the Information Age,” http://www.theclimategroup.org/

[3] Nedevschi S., Popa L., Iannaccone G., Wetherall D., Ratnasamy S., “Reducing Network Energy Consumption via Sleeping and Rate-Adaptation,” NSDI’08, San Francisco, CA, 2008, pp. 323-336.

[4] Bolla R., Bruschi R., Christensen. K., Cucchietti F. Davoli, F., Singh S., “The Potential Impact of Green Technologies in Next Generation Wireline Networks - Is There Room for Energy Savings Optimization?,” IEEE Comm. Magazine, vol. 49, no. 8, pp. 80-86, Aug. 2011.

[5] Bolla R., Bruschi R., Davoli F., Cucchietti F., “Energy Efficiency in the Future Internet: A Survey of Existing Approaches and Trends in Energy-Aware Fixed Network Infrastructures,” IEEE Comm. Surveys & Tutorials, vol. 13, no. 2, pp. 223-244, 2nd Qr. 2011.

[6] L. Noirie, “The Road Towards All-Opticall Networks”, OFC2003, FA1, pp. 615-616

[7] J. Berthold, A. A. M. Saleh, L. Blair, J. M. Simmons, “Optical Networking: Past, Present, and Future,” J. of Lightwave Tech., vol. 26, no. 9, May 2008, pp 1104-1118

[8] A. Tzanakaki, I. Wright and S. S. Sian, “Wavelength Routed Networks: Benefits and Design Limitations,” SCI2002, Orlando, Florida, Jul. 2002.

[9] Chikama et al, "Photonic Networking Using Optical Add Drop Multiplexers and Optical Cross-Connects", Fujitsu Sci. Tech., J., 35, 1, pp.46-55, July 1999.

[10] A. Tzanakaki, I. Zacharopoulos and I. Tomkos, “Broadband Building Blocks”, IEEE Circuits and Devices Magazine, vol. 20 , no. 2 , pp. 32-37, March-April 2004.

[11] A. Tzanakaki, I. Zacharopoulos and I. Tomkos, “Optical Add Drop Multiplexers and Optical Cross-Connects for Wavelength Routed Networks”, ICTON 2003.

[12] A. Dutta, N. Dutta & M.Fujiwara, “WDM Technologies: Optical Networks”, Volume III, Elsevier Academic Press, 2004.

[13] H. Pin-Han, H. T. Mouftah, “Routing and wavelength assignment with multigranularity traffic in optical networks”, J. of Lightwave Technology, vol. 20, no. 8, Aug. 2002, pp. 1292–1303.

[14] C. T. Politi, D. Klonidis, A. Tzanakaki, M. J. O’Mahony and I. Tomkos, “Novel Wavelength/Waveband Cross Connect Architecture based on Optical Wavelength Converters and a Passive Wavelength Router”, LEOS Annual mtg, 2003, vol. 1, pp. 140 – 141, October 2003.

[15] C. T. Politi, C. Matrakidis, A. Stavdas, D. Gavalas and M. J. O’Mahony, “Single-layer multigranular optical cross-connect architecture with conversion capability and enhanced flexibility”, J. of Opt. Net., vol. 5, no. 12, Dec. 2006, pp. 1002-1012

[16] D. Reforgiato, A. Lombardo, F. Davoli, L. Fialho, M. Collier, P. Donadio, R. Bolla, R. Bruschi, "Exporting Data-Plane Energy-Aware Capabilities from Network Devices toward the Control Plane: The Green Abstraction Layer" NOC’12, June 2012, Vilanova i la Geltru, Spain.

[17] ACPI Specification, http://www.acpi.info/

[18] IETF EMAN Working Group, https://datatracker.ietf.org/wg/eman/

[19] Bolla R., Bruschi R., Cianfrani A., Listanti M., "Enabling Backbone Networks to Sleep," IEEE Network Magazine, vol. 25, no. 2, pp. 26-31, March-April 2011.

[20] ECONET, Deliverable 4.1, “Definition of energy-aware states,” URL: https://www.econet-project.eu/Deliverables