Traffic variation-aware networking for energy efficient optical communications

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***Abstract*— ‘Traffic-aware’ networking is a solution allowing the improvement of the energy efficiency of optical networks. The implementation of these networking schemes makes possible to adapt the number of fully powered systems to the amount of carried traffic. Various traffic-aware schemes are available in the literature; some acting on the optical amplifiers, others on the optoelectronic (OE) devices. In this paper we introduce the parameter ρ to measure the energy savings introduced by a ‘traffic-aware’ scheme; the savings are obtained by considering the maximum power required to transport the peak traffic and the average power required by the network to transport the traffic during a defined time-frame (e.g. day, week). The higher the ρ-parameter is, more energy-efficient the ‘traffic-aware’ solution is. The energy efficiency of three on-off strategies, acting separately and/or jointly to amplifiers and OE-devices, are compared and discussed in terms of management implementation and network resiliency.**

***Index Terms*— Optical Networks, Energy Efficiency.**

I. INTRODUCTION

THE current traffic network is growing annually with an annual pace of around 40% and for the next decade this trend will slightly decrease to 30% [1]. It was also demonstrated that this traffic increase will produce a rise in the energy consumption of the overall network with the following relationship: in the next 10 years an increase of 1200% of traffic will correspond to an increase of 150% of energy [2]. Moreover, in [2] it was also demonstrated that the energy consumption distribution will not follow the same share than today. Currently, the access network consumes up to 70% the overall network consumption and the backbone only 15%, in 2017 the power sharing will be 38% and 42%, respectively. Hence, it becomes imperative to find more energy efficient solutions also for the backbone. Such solutions have to be based on new paradigms in both the network/system design (i.e. disruptive architectural solutions and innovative equipments/devices) and operation management (i.e. protocol improvements), for jointly acting at both device and network levels.

The first step to well understand how to get the network more energy efficient is to observe the traffic behaviors. It has been observed that beside its exponential growth, it also presents predictable (i.e. daily, weekly) variations. On the contrary, optical networks are quasi-static, as all network elements are fully powered for the peak traffic (including over-provisioning), without considering the actual transported capacity. It appears evident that the first step for improving the energy efficiency in a network will be the possibility of adapting the number of devices powered in a network as a function of the traffic to be actually carried.

In this paper we present in Section II the definition of *traffic-aware networking* approach. The energy savings that are expected by only considering the traffic variations and the real energy savings that are related to the implementation of different possible strategies are discussed. In Section III we focus on one possible traffic-aware strategy that consists on the introduction of sleep-mode to the optical layer devices and three possible implementations. In Section IV we present the evaluation of the energy savings obtained with this three implementation and compare them. Section V presents some conclusions.

II. TRAFFIC AWARE NETWORKING

‘Traffic-aware’ networking denotes the capability of the network management to adapt the number of used devices to the amount of carried traffic. As ‘traffic-aware’ networks have not to be more expensive than current static networks, they have to be dimensioned so as to carry the peak traffic. Into operation, the ‘traffic-aware’ networking guarantees the activation/deactivation of a number of resources, both at the IP and at the Wavelength Division Multiplexing (WDM) layers, according to amount of incoming client’s traffic. If appropriate protocols, allowing a dynamic power management of the resources in the network are implemented, such networking strategy will allow energy savings at the network level.

A. ‘Traffic-aware’ networking strategies

Diverse works are available in the literature investigating various design strategies enabling the adaptation of the optical network state to the traffic variations. Regarding backbone networks, up to now, two main approaches have been identified: 1) data rate adaptive optical devices (also called elastic) [3]; and 2) sleep-mode of network devices [4]. Specifically, optical systems eligible for sleep-mode are opto-electronic (OE) devices (such as line-cards [5] and

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transponders (TSP)/regenerators (REG) [6]), IP-router and WDM chassis, [5] and amplifier sites [7], as they mainly contribute to the energy consumption in the backbone network [8].

Nevertheless, fully traffic-aware networks are difficult to plan and operate. Hence it becomes important to understand how much adaptive a strategy has to be.

To do this, in the following we propose the use of two parameters. The first defines the ideal energy savings that can be expected (ρ) as a function of the transported traffic, given a traffic variation profile and the device power consumption; these savings are not related to a specific implementation of a traffic-aware strategy. The second parameter (η) gives the energy savings directly related to the chosen traffic-aware strategy and the considered scenario (network topology, resilience strategies, etc.).

In the present paper we only compare traffic-aware strategies that are based on the sleep-mode approach. Moreover, we restrict our analysis to the sleep-mode fulfilled at the WDM layer, where only OE-devices, such as transponders, regenerators and amplifier sites have sleep-mode capabilities.

B. *Efficiency of a 'traffic-aware' networking strategy*

In an ideal network one can suppose that the power consumption (*P*) exactly follows the amount of carried traffic (*T*) at the time *t*. If we suppose that it is possible to completely switch off the network when it does not transport any traffic, the power-traffic relationship equals to:

$$P(t) = K \cdot T(t) \tag{1}$$

with *K* a constant value expressed in W·s/bit. However, since a residual power (P_{down}) has to be considered because some devices have to be powered to ensure the correct network operation (i.e. network/device monitoring and management), the relationship becomes:

$$P(t) = P_{down} + K \cdot T(t) \tag{1bis}$$

Being T_{peak} the maximum traffic value in a considered time frame and P_{peak} the resulting required power, the K parameter becomes:

$$K = \left(P_{peak} - P_{down}\right) \Big/ T_{peak} \tag{2}$$

Current optical networks (hereafter, reference case, *ref*) are unable of tuning their power consumption to the actual transported traffic, consuming as if the peak traffic is always carried:

$$P_{ref}(t) = P_{peak} \tag{3}$$

The energy efficiency (ε) provided by a 'traffic-aware' network operation is expressed in comparison with a reference scenario [9]; considering the power-traffic relationships given in equation (1bis), ε becomes:

$$\varepsilon(t) = \frac{P(t)}{P_{peak}} = \frac{P_{down} + K \cdot T(t)}{P_{down} + K \cdot T_{peak}} = \frac{P_{down} + \dfrac{P_{peak} - P_{down}}{T_{peak}} T(t)}{P_{peak}} \tag{4}$$

From (4) lower ε indicates smaller power consumption for a given traffic amount, *T(t)*. The average energy efficiency in a given time-frame will only depend on the average traffic:

$$\overline{\varepsilon} = \frac{P_{down} + \dfrac{P_{peak} - P_{down}}{T_{peak}} \overline{T}}{P_{peak}} \tag{5}$$

Besides the efficiency, the savings brought by the new solution with respect to a reference case can be highlighted. These savings can be expressed as ρ=1-ε; hence from equation we obtain:

$$\overline{\rho} = 1 - \frac{P_{down} + \dfrac{P_{peak} - P_{down}}{T_{peak}} \overline{T}}{P_{peak}} = \frac{P_{peak} - P_{down}}{P_{peak}} \cdot \left(1 - \frac{\overline{T}}{T_{peak}}\right) \tag{6}$$

We notice that the energy savings provided by 'traffic-aware' networking depend on:

- The gap between the average and peak traffic values: lower it is, smaller savings can be achieved;
- The ratio between P_{peak} and P_{down}: higher it is, major savings are obtained. [9] shows how the energy efficiency changes with respect to P_{down}/P_{peak}.

It is noteworthy that in a real network there is not a linear power-traffic relationship. In fact the traffic has a smaller granularity compared to the devices deployed in a network (e.g., client traffic granularity is of hundreds Mb/s up to some Gb/s, while in the network optical channels have up to 100Gb/s capacity and links supports up to 90 channels; hence power reduction cannot follow small traffic variations. On the other hand, a demand requires a number of devices (e.g. regenerators, amplifiers) that depends on the distance it has to travel. Finally for ensuring a certain level of network resiliency some traffic replication can be required as a function of the Quality of Service of the different services. On the basis of this consideration, a different energy savings parameter (η) that only considers the whole network power must be defined:

$$\eta(t) = \frac{P_{peak} - P\big(T(t)\big)}{P_{peak}} \tag{7}$$

$$\overline{\eta} = \frac{P_{peak} - \overline{P}}{P_{peak}} \tag{8}$$

Where $\overline{P}$ is the average power required by the network in a given time-frame.

Thanks to $\overline{\eta}$ we can compare different traffic-aware networking strategies. Moreover, this parameter enable to understand how far these strategies are from the ideal case (given by $\overline{\rho}$) so as to understand if other energy efficient improvements are possible.

III. SLEEP-MODE APPROACHES

In this section we briefly describe the three strategies that will be compared in this work: one considers the power management of only EO devices, another proposes the power management of only in-line amplifiers and the last one allows both power policies at the same time.

A. Link sleep-mode approach

The Link sleep-mode approach (LSM) turns down (sleep mode) all optical amplifiers present on unused links. This is generally supported by the assumption that the wake-up time of the optical amplifiers is short enough to meet the Label Switched Paths (LSPs) setup time requirements.

In Wavelength Switched Optical Networks (WSONs) controlled by GMPLS protocols, the LSM support has been also investigated [7]]. There, centralized and distributed strategies to dynamically select the WDM links to be set to sleep mode were considered, aiming to sleep as many fiber links as possible, while still carrying the offered traffic to the network. This approach tends to aggregate active LSPs, in order to set low loaded links in sleep mode. Therefore, while some power savings can be achieved for low traffic loads, this operation impacts on the robustness of the network against link failures. In fact, by setting links to sleep mode, the connectivity of the network decreases. This may compromise efficient recovery actions in case of failures [10]. Apart from this, the dynamic LSM management requires the re-routing of all the supported LSPs when a link power status is changed (using make-before-break strategies), which requires additional routing and signaling actions and, eventually, more complexity at the GMPLS network control plane. The power status of OE devices (Add/Drop transponders (TSPs) and regenerators (REGs)) is not modified in this approach; they remain always powered, even if no LSP is supported.

B. OE device-sleep mode approach

The dynamic power management of OE devices (OESM) has also been proposed, jointly with the GMPLS routing and signaling protocol extensions enabling it [6], [11]. Hereafter, we refer to this approach as the OE device-sleep mode (OESM). OE devices can be totally or partially powered (up and idle states, respectively) or switched off (down state). In up state, devices are fully powered and operational, whereas in down state they are unpowered and unused. In the intermediate idle state, devices are non-operational but semi-powered, that is, keeping those components requiring thermal stabilization powered on for fast wake-up time (few tens of ms [6]). With this approach, the link power status is not modified, that is, optical amplifiers are always powered, even when not supporting any active LSP.

C. Hybrid sleep-mode approach

The hybrid sleep-mode (HSM) approach considers the power management of both OE-devices and links. This approach allows us to understand if more complex approaches provide further energy savings or not.

IV. TRAFFIC-AWARE STRATEGIES CASE STUDY

This section quantitatively estimates the energy savings provided by the above mentioned strategies. In [12], we reported the network power consumptions for two different network topologies and traffic loads ranging from 10 to 100% of the peak traffic, which equals the maximum amount of traffic that the network can support avoiding any request blocking. The number of requests routed for the unprotected scenario is almost twice the number of requests served in the protected case, because in this latter case to one request two paths (working and protection) are associated. The results reported in [12] are obtained by the use of a Mixed Integer Linear Programming (MILP) formulation performing a translucent optical network planning which minimizes the power consumption at the optical layer. The model presented in [12] considers 1:1 protected scenario; the unprotected case has been obtained by reducing in the formulation the set of parameters K (representing the working and protected path) to only one element.

For low traffic periods, two different network re-design methods are proposed: a) the lightpaths in low-traffic periods are a subset of the ones established for the peak traffic, this method is called *static-case* (*SC*) in the following; b) the lightpaths in low-traffic periods can change so as to minimize the whole network power consumption, this method is called *dynamic-case* (*DC*).

A. Simulation hypotheses

1) Network scenarios

The comparisons of the traffic-aware strategies considered in this study are performed on a Pan-European network topology, namely the COST-239 one [13]. The features of this network are summarized in Table I.

Table I: Cost-239 characteristics [13].

Parameter	*Value*
Number of nodes	11
Number of links	22
Average node degree	4
Average link length (km)	421

About the traffic matrices, the peak-traffic is obtained by generating a set of random selected demands, drawn with a uniform distribution. For a specific network scenario, the same peak-traffic is used for energy planning achieved with the different traffic-aware strategies. When lower traffic loads are considered, we selected a percentage of the peak traffic demands in a random way and resources relative to unused requests are released and set at sleep-mode if possible. Low traffic loads range from 10% to 90% of the peak traffic with a step of 20%... Three different traffic variations (daily) are accounted, whose profiles are reported in Figure 1, while the corresponding average and minimum traffic values are reported in Table II.

Table II: Daily traffic variations measured by different network operators.

	Average	*Minimum*	*Maximum*	*Reference*
Orange	61%	14%	100%	[3]
Amsterdam	72%	30%	100%	[14]
DT	15%	5%	100%	[15]

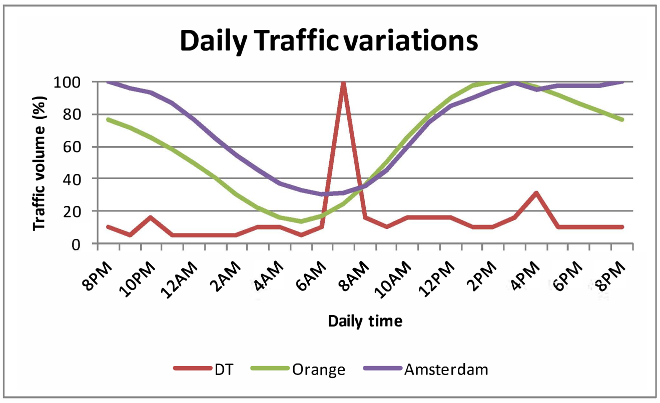

Figure 1: Daily traffic variations measured by different network operators.

2) *Energy consumption assumptions*

For OE devices, we consider the model proposed in [6] based on a PDM-QPSK 100Gb/s transponder. For such transponder the energy consumption values: in up-state, OE devices consume: 351W for TSPs and 414W for REGs; in idle-state the power consumption drops to 18W for TSPs and to 36W for REGs, respectively. For amplifier sites, the same model for both in-line and node amplifiers is assumed. An amplifier site typically consumes 287W; it is composed of two EDFA modules (one per each fiber directions) including monitoring of the input and output power and management system (100W each); the two EDFA modules are contained in a shelf, comprising a power supply (10W), management of the amplifier sites (17W) and fans (60W), which allow the thermal control of the module.

B. *Numerical results*

Figure 2 shows the power consumptions related to the unprotected (a) and 1:1 protected (b) scenarios. The grey curves represent the static ('sc' in the figure legends) case, while the black ones the dynamic one ('dc' in the figure legends). For the OESM scenario, only the static case is considered, as for the dynamic case we observed almost the same results (improvements <0.1%), because savings are only due to the possibility of skipping some intermediate regenerators. From Figure 2 we observe that unprotected and 1:1 protected scenarios behave in a linear way, with different linear slopes (*K* factor of equation 2) for HSM and OESM strategies (*K* value for the protected scenario is twice the one relative to the unprotected scenario). We also observe that for the peak traffic the maximum power requirement is 63% lower for the HSM and OESM strategies, mainly due to the fact that without failure unused OE devices are set to idle mode (which consume 90% lower than a fully powered OE device). Results also show that dynamic reconfigurations provide further savings when link power management operates.

Now, to estimate the impact of the presented traffic-aware approaches with the daily traffic variations reported in Figure 1, we consider the power required to a given traffic value. We assume network reconfigurations occur every time the traffic profile scales up/down of 5% with respect to the peak traffic value and with a minimum time spacing of 30 minutes.

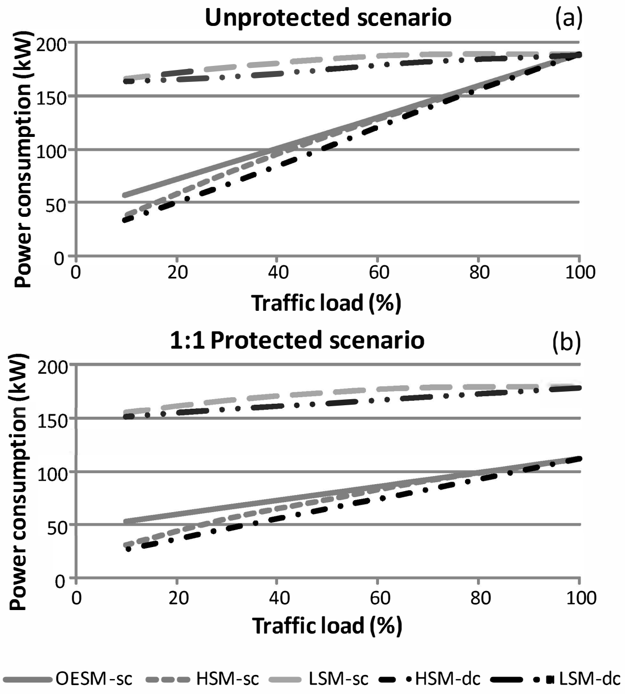

Figure 2: Power consumption as a function of the transported traffic, (a) for unprotected and (b) for 1:1 protected scenarios.

Figure 3(a), Figure 3(b), and Figure 3(c) report the daily power consumptions for the proposed approaches without (left-hand side) and with (right-hand side) protection assumptions. We observe that all strategies adapt their power consumption to the transported traffic, but they differentiate on how closely they track traffic fluctuations. It appears that LSM strategy hardly allow power savings (average savings of 5%, mainly observed with the dynamic scenario); important savings are reported for very low daily average traffic (DT traffic profile), reaching 12% of savings. Generally, HSM outperforms OESM only when traffic loads lower than 55%, from ~10% for 50% of traffic loads up to ~50% for 10% of traffic loads.

Finally, to compare the efficiency of the proposed methods, we compute both $\overline{\eta}$ and $\overline{\rho}$ for the different traffic-aware networking following the three considered traffic fluctuations. Results are summarized in Table III. Comparing the $\overline{\eta}$ values, we confirm that link power management is far away from providing savings with respect to traffic fluctuations. Moreover we observe that for the 1:1 protected scenario, savings higher than the ideal ones are reported. This is due to the fact that for the reference case, resources associated to the protection path have to be powered even if no effective traffic is transmitted, resulting in transmitting an amount of traffic that is twice the required one and doubling the power requirements of OE-devices. In fact, in current networks no protocol enhancement enabling an automatic device powering is implemented. This waste of energy is also verified in LSM strategy. In [11] we demonstrated that setting transponders in idle-state, the transition from idle non-operating to up fullyoperating state result in average ~10ms, that is compatible with the restoration requirement of gold-class services. Setting protection OE-devices at idle-state provide huge power savings, solving one of the major energy problems in optical network transmission: the path redundancy for resilience purpose. From Table III we also observe that for the protection scenario LSM power gains are more important compared to the unprotected scenario. We observe that the possibility of setting the OE-devices associated to the protection path to idle-mode allow savings that are almost doubled compared to the unprotected case. This is due to the fact that for the protection scenario, half of the available resources ensure the duplication of data for the protection, one of the main wastes of energy in current optical scenario. When we consider traffic fluctuation, the ρ value relates to the real amount of transported traffic, does not consider traffic duplication. This is the reason why the 1:1 protected scenario provides higher values of power savings: now redundancy is accounted.

From Table III we also observe that the HSM strategy outperforms OESM of around 5% when no further dynamics are allowed (SC reconfiguration) and for the unprotected scenarios. The HSM outperforms OESM up of 20% when further reconfiguration is provided.

Now, from a point of view of a network one has to understand the trade-off on the operational cost associated to the reconfiguration and the improvement of the energy efficiency. We consider that reroute a connection means to activate some maintenance on the path during the reconfiguration. This operation requires further costs that are not considered in this study and moreover can jeopardize the correct network operation. For this reason, we think that OESM is a good trade-off between energy efficiency, and system power reconfiguration and connection rerouting.

Table III: Energy savings provided by the proposed traffic-aware networking with static (SC) and dynamic (DC) optical connection reconfiguration.

η for Orange Traffic Variations (%)

	LSM		OESM		HSM		Ideal (ρ)
	SC	DC	SC	DC	SC	DC	
Unprot.	2.4	5.7	28.6	28.6	30.4	33.8	36.7
1:1 prot.	3.0	6.5	50.9	50.9	53.5	56.6	

η for Amsterdam Traffic Variations (%)

	LSM		OESM		HSM		Ideal (ρ)
	SC	DC	SC	DC	SC	DC	
Unprot.	1.8	4.4	21.9	21.9	22.7	25.8	28.1
1:1 prot.	1.8	5.1	47.8	47.8	49.1	52.1	

η for DT Traffic Variations (%)

	LSM		OESM		HSM		Ideal (ρ)
	SC	DC	SC	DC	SC	DC	
Unprot.	8.2	11.6	58.1	58.1	64.6	68.6	74.6
1:1 prot.	9.6	12.8	64.6	64.6	73.4	76.3	

V. CONCLUSION

Energy-efficient solutions form communication networks are mandatory due the expected traffic growth for the next decade. This traffic growth will produce an increase of the energy consumption of the backbone network. At the same time, it has been observed that the traffic present fluctuations, some of them predictable, while the network operate in a static manner. Hence, to cope with an excessive need of energy, various energy-efficient solutions have been proposed, so as to consume proportionally to the amount of effective traffic. Such solutions are named ‘traffic-aware’. In this paper we propose a method for comparing the various ‘traffic-aware’ strategies, so as to account the network scenario, the traffic fluctuations, the power savings and the complexity relative to the different approaches.

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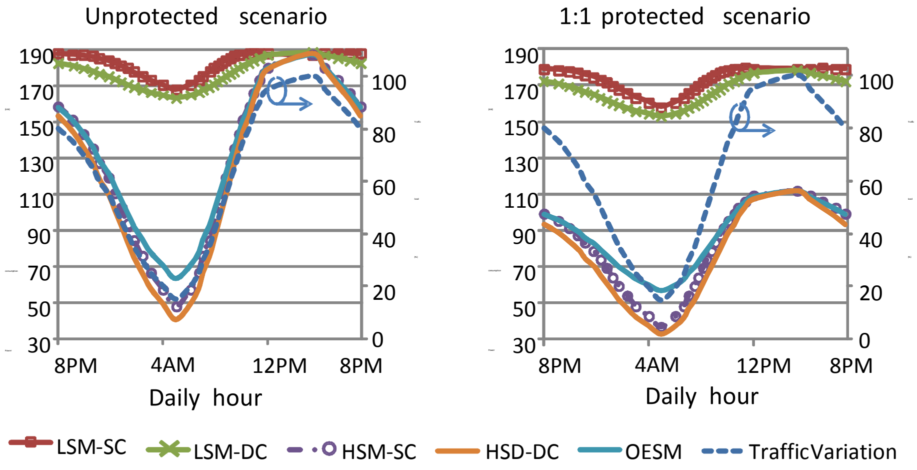
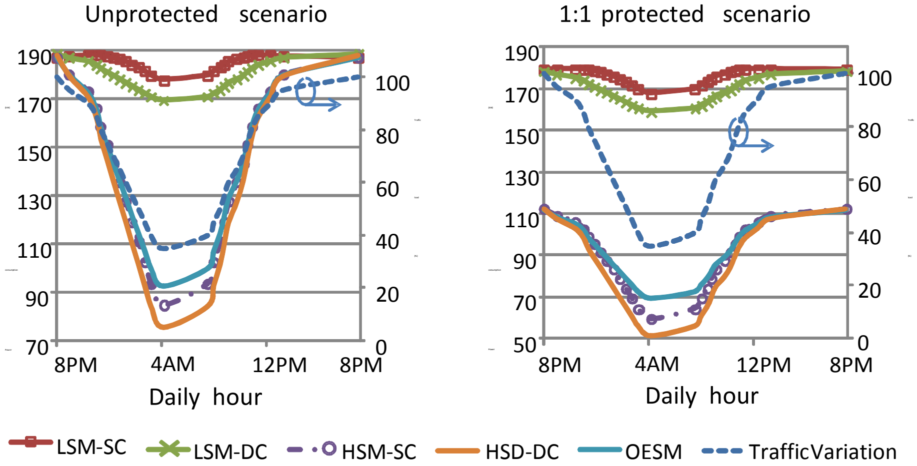

(a) OrangeTrafficVariation


(b) AmsterdamTrafficVariation

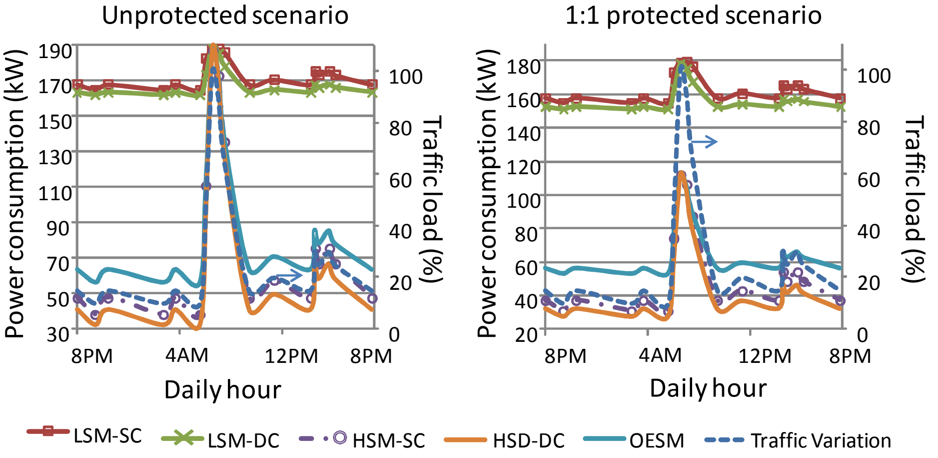

(c) DT Traffic Variation

Figure 3: Daily power consumption for the European COST network as a function of the used power strategies. Power consumptions are estimated considering three different traffic fluctuations measured by Orange (a), DT (b), and Amsterdam (c).