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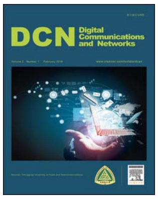

Will video caching remain energy efficient in future core optical networks?

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ABSTRACT

Optical networks are expected to cater for the future Internet due to the high speed and capacity that they offer. Caching in the core network has proven to reduce power usage for various video services in current optical networks. This paper investigates whether video caching will still remain power efficient in future optical networks. The study compares the power consumption of caching in a current IP over WDM core network to a future network. The study considers a number of features to exemplify future networks. Future optical networks are considered where: (1) network devices consume less power, (2) network devices have sleep-mode capabilities, (3) IP over WDM implements lightpath bypass, and (4) the demand for video content significantly increases and high definition video dominates. Results show that video caching in future optical networks saves up to 42% of power consumption even when the power consumption of transport reduces. These results suggest that video caching is expected to remain a green option in video services in the future Internet.

1. Introduction

The number of Internet users has grown to over 2.8 billion users [1] and Internet traffic is expected to exceed 1 Zettabytes (1 billion Terabytes) in 2016 with an annual growth rate of about 21%[2]. In a few years, video content is estimated to account for 80–90% of the total IP traffic, and on average one million minutes of video content is projected to cross the Internet every second [3]. Energy consumption is predicted to become the new Internet bottleneck of communication networks. Data centers which mange and provide content are a critical part of the Internet and consume significant energy – up to 70% of the total transmission energy [4]. These alarming figures depict the increasing energy consumption of the Information and Communication Technology (ICT) industry, thus implying increasing associated carbon dioxide (CO_2) emissions. ICT's CO_2 emissions are expected to increase from 0.5 billion tons in 2002 to 1.4 billion tons in 2020 [4], exceeding 3% of global emissions [5]. The possible environmental impacts of the Internet expansion have boosted a global movement towards reducing the CO_2 footprint of ICT.

One successful strategy in video service power reduction is content caching. The main objective of caching is to reduce traffic on the communication path between the data center and users by storing videos closer to the users. Due to their limited storage capacity, caches contain a small amount of the whole video library. As a result, it is important that they maintain the most popular content to maximize traffic served from caches.

Future optical network technologies are overviewed in [6,7]. It is likely that future networks will become all optical with intelligent ultra long-haul optical transmission. Future optical networks are expected to implement hardware improvements in laser, transmitter/receiver, amplification and multiplexing technologies [6,7]. The main focus of these reviews and similar studies is the potential increase in network speed and capacity. However, there is still a need to assess the improvements in network performance considering expected growth in carried traffic.

Prior studies have proposed improvements to current optical networks that are expected to reduce power consumption when implemented. The authors of [8] proposed a server provisioning strategy for a Video-on-Demand (VoD) service that turns on/off servers with respect to traffic load. This strategy uses a proactive online algorithm to calculate the predicted number of requests at each time. The number of requests is used to compute expected traffic. With more focus on Wave Division Multiplexing (WDM), the proposed models in [9–11] evaluate the energy consumption of optical core networks considering switch on/off techniques and optical bypass. In [12] the power consumption of an IP over WDM network is minimized by optimizing the cache sizes deployed at network nodes. The work however does not identify whether caching is expected to remain power efficient under future optical network improvements. The work in this paper explores this issue.

To the best of our knowledge, no prior work has compared the power efficiency of caching considering current and future networks. This paper evaluates the power consumption of caching in an IP over WDM core network. It takes into account an optical network with present features and calculates the power consumption as a result of

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caching popular content at the core nodes. The power consumption is compared to future optical networks to predict the survivability of caching in the future Internet. Future networks are represented by highlighting four features where one or more feature is implemented in the network and compared to current network settings.

The evaluation in this paper states that: (1) future network hardware is equipped with traffic adaptation capabilities where inactive parts of devices are put in sleep-mode when traffic is low, (2) future network components consume less power compared to today's networks, (3) future networks utilize lightpath bypass when implementing IP over WDM where intermediate IP routers on the communication path are avoided, and (4) the average video traffic in future networks is significantly higher compared to today's networks. Content caching is considered under all scenarios and the power consumption of the network is evaluated. We also evaluate the power consumption of an optical network combining all considered current network features. The power consumption is compared to that where a network implements combined future optical network features. Finally, we evaluate daily energy savings due to caching.

The remainder of the paper is organized as follows. The following section explains IP over WDM and its implementation options. Next, future optical network characteristics are highlighted. The subsequent section demonstrates the results of the power consumption evaluation. The final section is a conclusion.

2. Implementing IP over WDM

Internet Protocol (IP) is expected to remain the revenue generating technology, favored by all end user communication [13]. At the same time, Wave Division Multiplexing (WDM) provides increased capacity using existing fiber cables and hence with no significant increase in the network cost. Therefore WDM is the ideal solution for optical network expansion. The attractive features offered by IP and WDM result in IP over WDM being a strong candidate to cater for the next generation Internet.

A lightpath is a point-to-point all optical wavelength channel connecting a source and a destination [14]. There are two strategies that can be employed when implementing IP over WDM considering the manner that a lightpath traverses IP routers. These strategies are Lightpath non-bypass and Lightpath bypass, and are shown in Fig. 1.

1) Lightpath non-bypass.
   When this type of IP over WDM is implemented, all the IP routers of intermediate nodes on the path from the source node to the destination node are traversed, engaging IP router ports on each intermediate node (see Fig. 1a). Current optical networks employ lightpath non-bypass routing.
2) Lightpath bypass.

When lightpath bypass is considered, traffic passing through an intermediate optical node is forwarded to the next optical node bypassing the IP router of the intermediate node (see Fig. 1b). This approach requires intelligent optical switches capable of identifying the destination node of the traffic flow and the next node on the route on which the traffic is forwarded. In addition, this strategy is considered to be more power efficient, as less power-consuming IP router ports are activated. Lightpath bypass results in higher power savings compared to lightpath non-bypass. However, the downside is that it does not enable the operator to access data at intermediate nodes for security deep packet inspection and correction, and so some video services opt to implement lightpath non-bypass [15].

3. Current and future optical core networks

In this work, we take into account a number of optical network features to exemplify future networks. We investigate the energy efficiency of caching with respect to current and future networks. This section explains the features that characterize future optical networks, and are summarized in Table 1.

3.1. Network equipment with sleep-mode capabilities

Network devices such as switches and routers are capable of providing high-capacity connectivity when working at full utilization. In practice, these devices do not operate at full capacity most of the time, wasting unnecessary resources. When sleep-mode capable equipment is used, network resources are provisioned with respect to instant traffic, minimizing power use and cutting down service costs.

Currently, most networks do not utilize equipment with sleep-mode capabilities. Even though sleep-mode capable network switching and storage devices are available, a number of reasons result in decreasing the popularity of these devices. One reason is the additional network overhead produced by these devices, since device controllers need to be aware of instantaneous traffic measurements to accurately switch on/off device segments.

Another reason is the delay that a device suffers when it goes from sleep-mode to becoming fully active. This delay is larger when device sections are switched off when inactive rather than put in sleep-mode. The resulting delay causes momentarily request rejections due to lack of resources when network traffic increases. Request rejections occur because the network elements responsible for handling the traffic generated by additional requests are in the waking-up phase.

Networks that deploy devices with no traffic adaptability facilities provision network resources for maximum traffic. Network equipment operates at full power all the time regardless of instantaneous traffic, consuming unnecessary power when the traffic is low.

Hardware advancements are expected to produce sleep-mode capable network devices with fewer downsides, expanding their implementation and allowing networks to utilize more power efficient equipment. In this work the gain of caching is explored considering both types of network devices.

Under current networks, only caches of fixed sizes can be deployed where a cache of a fixed size is operating all the time. In contrast, when sleep-mode capable devices are implemented, caches adapt to instantaneous traffic resulting in a different cache size over time (variable caching [12]).

3.2. The power consumption of network components

When the power consumption of streaming content from a data center is high, caching is considered beneficial. In contrast, caching wastes unnecessary power if the power consumption of storing popular videos in caches exceeds that of streaming them from data centers. The IP router port is the most power consuming element in the network. Therefore the power consumption of an IP router port is considered as the decisive factor of whether to stream a video from a remote data center or to store it in a local cache.

The power consumption of other components in the network such as amplifiers, transponders, switches and multiplexing equipment also influences the power consumption of the network and the caching decision. However, since the IP router port consumes considerably more power compared to other network components (1000 W per IP router port versus 8–85 W for other components), this study therefore takes into account IP router ports only.

The evaluation considers two recent values for the power consumption of a router port to investigate the influence of the decrease in the power consumption of transport on the significance of caching.

3.3. IP over WDM implementation

Under lightpath non-bypass, IP router ports are engaged at each intermediate node that traffic traverses. In contrast, under lightpath bypass, traffic is forwarded to the next optical node on the path without

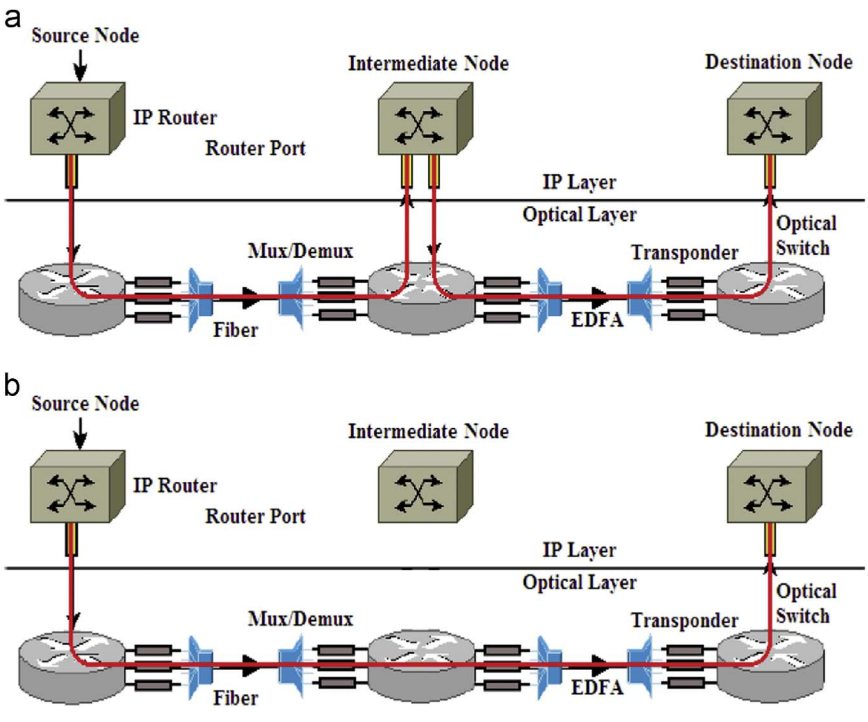

Fig. 1. IP over WDM implementations: (a) lightpath non-bypass, and (b) lightpath bypass.

Table 1
Current and future network features.

Feature	Current networks	Future networks
Power consumption of network components	Higher	Lower
Sleep-mode capabilities	No sleep-mode capabilities	Sleep-mode capable equipment
IP over WDM implementation	Lightpath non-bypass	Lightpath bypass
Video traffic	Low demand delivered at SD	High demand delivered at HD

occupying IP router ports at that node. This difference implies that no power is consumed by IP router ports at intermediate nodes under lightpath bypass. Since IP router ports are major power consumers, the difference in the IP over WDM implementation is bound to influence the power consumption of the network. It is expected that employing lightpath bypass will result in reducing the power consumption of accessing video content remotely.

The question that comes to mind is whether the reduction in the power consumption of transport introduced by implementing lightpath bypass eliminates the need for caching. This study compares the power consumption of the network under the two considered IP over WDM implementations and investigates whether deploying caches at the nodes results in similar power savings under the two strategies.

3.4. Network video traffic

The popularity of Internet video applications has resulted in a continuous increase in video demand. It is expected that video traffic will account for 80% of all Internet consumer traffic by 2019 [2]. Consequently, it is important to evaluate the influence of increasing video traffic on network performance for reliable predictions and safe network expansion and scalability. The amount of video traffic on the network is influenced by the total number of requests and the size (or length) of each video. Caching reduces the communication path between the source and destination by storing popular content closer to end users. The number of videos to store in caches depends on the total number of videos and their popularity distribution [12]. This work studies the influence of increasing the video demand in the network combined with increasing in the average sizes of video files. The reason for this combination is that future networks are expected to cater for a greater number of users downloading larger videos due to the domination of high-definition video. The work finds the power consumption of the network with moderate demand for Standard-Definition (SD) videos and compares it to the power consumption of delivering High-Definition (HD) video requested at a high rate.

4. Power consumption evaluation

To evaluate the power consumption comparing current and future networks, we consider video caching in an IP over WDM core network. The power consumption of the network is the sum of the power consumption of IP router ports, transponders, EDFAs, optical switches, multiplexers/demultiplexers and caches. In Table 2, the power consumption values of the network components are shown. The power consumption evaluation is carried out by minimizing the power consumption of the network by optimizing the amount of content stored in core caches. This is achieved using a Mixed Integer Linear Programming (MILP) model. The MILP model is based on the power minimization model proposed in [9] and is extended to include video caches, upload and download traffic and to take into account the IP over WDM implementation option (lightpath bypass and lightpath non-bypass).

Table 2
Input data.

Distance between two neighboring EDFAs	80 (km)
Number of wavelengths in a fiber	16 [9]
Capacity of a wavelength	40 (Gb/s)
Power consumption of a router port	1000 (W) [18]
Power consumption of a transponder	73 (W) [9]
Power consumption of a multiplexer/demultiplexer	16 (W) [19]
Power consumption of an EDFA	8 (W) [20]
Power consumption of an optical switch	85 (W) [21]
Power consumption of a cache	7.4 (W/GB) [12]

The power consumption evaluation in [9] considers lightpath bypass, and therefore the power consumption of IP router ports PR_i at node i is given as

$$PR_i \;=\; Pp\bullet \sum\nolimits_{j\in N} C_{ij} \tag{1}$$

where Pp is the power consumption of a router port, N is the set of nodes and C_{ij} is the number of wavelengths on the virtual link between node i and j. Our work here compares lightpath non-bypass and lightpath bypass. Therefore, the MILP model in this work uses an alternative equation to calculate the power consumption of router ports. The power consumption of router ports at node i when lightpath bypass is implemented is defined as

$$PR_i \;=\; Pp\bullet \sum\nolimits_{j\in N} w_{ij} \tag{2}$$

where w_{ij} is the number of wavelengths on the physical optical link between node i and j.

Regular traffic (non-cacheable traffic) between node pairs is generated using a random function having a uniform distribution on the interval (10 Gb/s, 230 Gb/s). In addition to regular traffic, video traffic is considered where videos can be uploaded and downloaded to and from data centers, respectively. The ratio of download traffic from a data center to a node to regular traffic Δ_d and the ratio of upload traffic from a node to a data center to regular traffic Δ_u are generated based on the regular traffic demand and are considered to be (1) Δ_d=1.5 and Δ_u=0.2 and (2) Δ_d=7.5 and Δ_u=1.0 of the regular traffic. These values match the input and output rates of a typical data center [16] and are suitable to evaluate video traffic growth.

The total network traffic is the sum of video and non-video traffic, and these traffic components are shown in Fig. 2. The model in [9] considers the regular traffic λ^{sd} from node s to d. Here, the traffic demand λ^{sd} is made up of regular traffic λr^{sd}, upload traffic λu^{sd} and download traffic λd^{sd} as follows:

$$\lambda^{sd} = \lambda r^{sd} + \lambda u^{sd} + \lambda d^{sd} \tag{3}$$

The upload and download traffic are defined as

$$\lambda u^{sd} = \lambda^{sd}\cdot\Delta_u\cdot\delta_d \tag{4}$$

$$\lambda d^{sd} \;=\; \lambda^{sd}\cdot\Delta_d\cdot\delta_s\cdot(1-hit) \tag{5}$$

where δ_s is 1 if node s has a data center and hit is the cache hit ratio. The download traffic from node s to node d is reduced by the amount of traffic served from the cache deployed at node d, calculated from hit.

Standard Definition (SD) and High Definition (HD) videos are delivered using the Motion Picture Experts Group 4 – Advanced Video Coding (MPEG-4 AVC) compression standard at 1.5 Mbps and 10 Mbps, respectively [17].

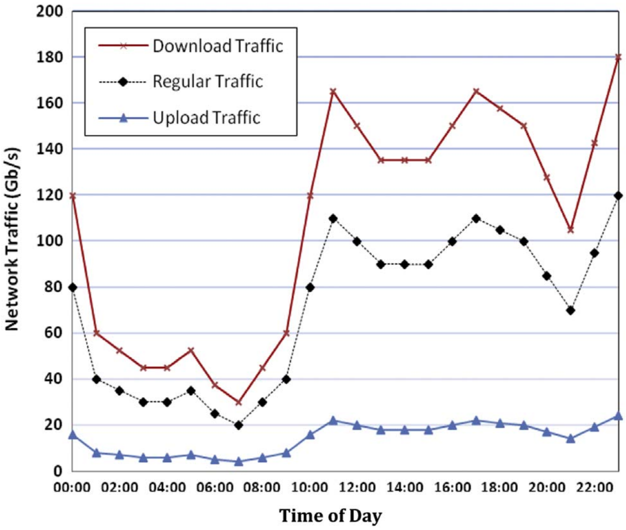

Fig. 2. Regular, upload and download traffic when Δ_d=1.5 and Δ_u=0.2.

The test network used in this work is the NSFNET topology having 14 nodes and 21 links, shown in Fig. 3. The figure shows fiber lengths in kilometers and the locations of the 7 data centers with unique video content requested by users at the nodes. The considered video service assumes a library of 2 million videos of the same size of 200 MB. The popularity distribution of videos follows a Zipf distribution. When fixed caching is considered, a cache of a fixed size of 100 GB is assumed to be deployed at each node. Considering variable caching, each node is equipped with a cache that adapts the size of its active part according to instantaneous nodal traffic.

4.1. Network equipment with sleep-mode capabilities

When network devices do not support resource adaptation, network resources are provisioned for the peak load. Consequently, these networks consume constant power, relative to the network peak traffic. Current networks mainly do not support sleep-mode capabilities. Caching significantly reduces peak traffic which could therefore lead to reductions in power consumption. However, the greatest benefits are not obtained until variable sized caches can be deployed which is not possible until sleep-mode capable equipment is installed. Future networks are expected to be able to adapt their resources by switching off any components that are not in use. This would reduce the power consumption when the traffic is low and therefore the network consumes the maximum power only when the traffic is at its peak.

Fig. 4 shows possible power savings due to caching with current and future networks. It shows the power consumption of the network with no sleep-mode capable equipment without caching and when deploying 100 GB caches at the nodes. It also evaluates these scenarios when devices have sleep-mode capabilities. In addition, it shows the power consumption of the network using variable caching.

The overall power consumption having sleep-mode capable equipment follows the trend of traffic. The maximum savings in power consumption are 38% using fixed cache sizes under current and future networks. These savings are similar due to the fact that maximum power savings considering future networks are achieved at peak traffic (the same traffic that current network resources are provisioned). Power savings due to variable caching are up to 42%. Note that deploying sleep-mode capable equipment saves significant power regardless of caching, with maximum savings achieved during off-peak hours.

4.2. The power consumption of network components (router ports)

In a matter of a few years, the power consumption of an 8-slot CRS-1 has dropped from 8000 W to 4834 W due to technology enhancements [18].The power consumption of a single 40 Gb/s port Pp is estimated by dividing the power consumption of the router over the number of ports [9]. Following this approximation, the power consumption of a router port has reduced from 1000 W to 604 W. Fig. 5 shows the influence of the router port power consumption Pp on the network power consumption with no caching and under variable caches with sleep-mode capabilities. It shows the same influence with no sleep-mode capabilities assuming no caching and under fixed cache sizes of 100 GB.

IP router ports are major power consumers, and therefore the power consumption of the network is less when router ports are more power efficient under no caching and variable caching. The power consumption of the network falls by 36% and 35% (maximum and average) under no caching and variable caching, respectively. Under variable caching, the optimum cache sizes that minimize power consumption averaged over the time of the day drop by 35% when Pp falls from 1000 W to 604 W.

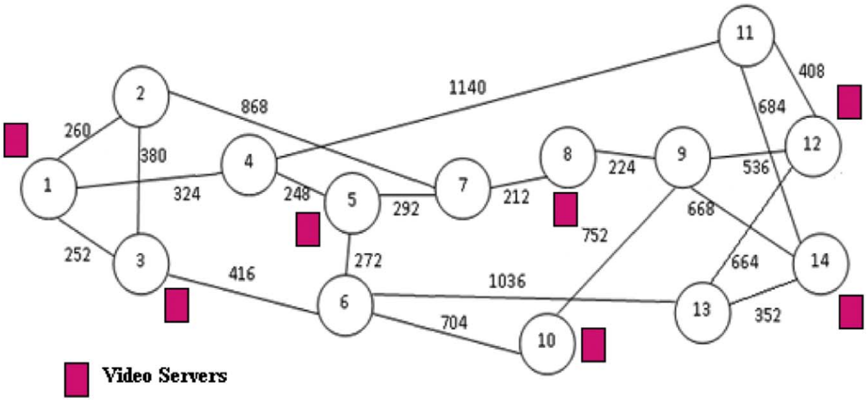

Fig. 3. The NSFNET topology with locations of data centers and fiber lengths (km) [9].

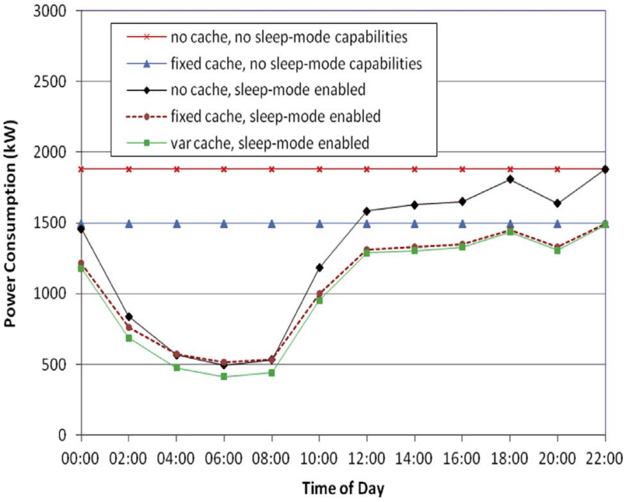

Fig. 4. Power consumption of the network considering no caching, caches of fixed sizes and variable caches assuming network equipment with and without sleep-mode capabilities.

When the power consumption of a router port is high, the power consumption to download a video from a data center to the requesting node is also high. In this situation it is more power efficient to store more videos in local caches. As *Pp* reduces, the feasibility of consuming more power on caching reduces. Nevertheless, the overall network power savings due to caching are similar considering the two values of *Pp* and are up to 42%. These savings are similar under current and future networks.

It is expected that network devices will continue to consume less power due to advances in hardware technologies. These hardware improvements are expected to include storage devices, reducing the power consumption of caching. Thus, caching is expected to remain a traffic reduction option.

4.3. IP over WDM implementation

The power consumption of the network under lightpath non-bypass and lightpath bypass considering no caching and variable caching with sleep-mode capable equipment is shown in Fig. 6. Fig. 6 also shows the power consumption of the network when no sleep-mode capable devices are deployed considering no caching and 100 GB caches at the nodes. Lightpath non-bypass consumes more power compared to lightpath bypass due to the additional power consumed in the IP layer (the IP layer includes router ports – the main power consumers).

Implementing lightpath bypass is more power efficient when the average number of hops from the content to requesting nodes is high. The maximum savings in power consumption under lightpath non-bypass and lightpath bypass are 46% and 42%, respectively considering both current and future networks. When variable caches are deployed on the network, the power consumption is minimized by deploying caches with an average size of 130 GB and 83 GB under lightpath non-bypass and lightpath bypass, respectively.

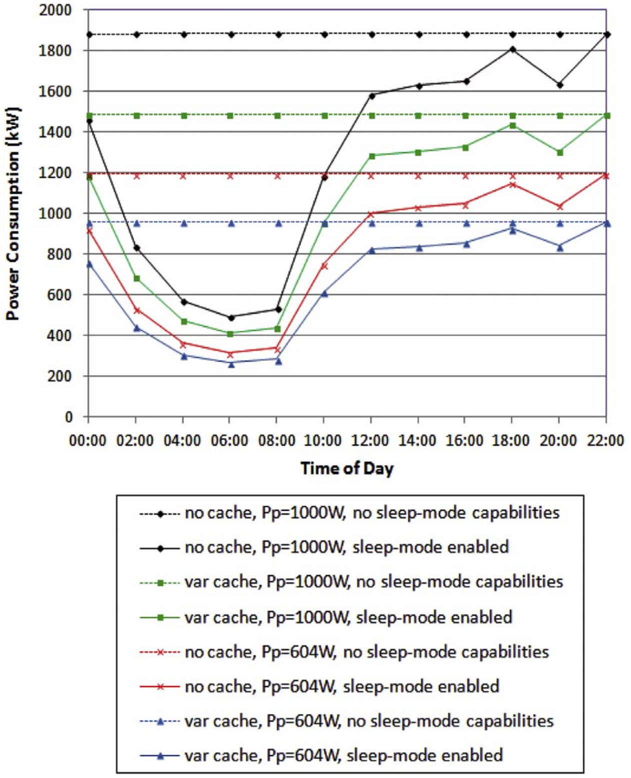

Fig. 5. Network power consumption with no caching and under variable caching considering previous and current values for the power consumption of a router port under current and future networks.

Lightpath bypass consumes less power on transport, favoring more videos to be downloaded from remote data centers. This explains the smaller cache sizes found by the MILP model under lightpath bypass. Yet, deploying these smaller caches results in more power efficiency compared to no caching, justifying their deployment in core nodes.

4.4. Network video traffic

The influence of video traffic on the power efficiency of caching is evaluated by comparing a current or future network. The current network is assumed with low demands for SD videos and the future network delivers highly demanded HD videos.

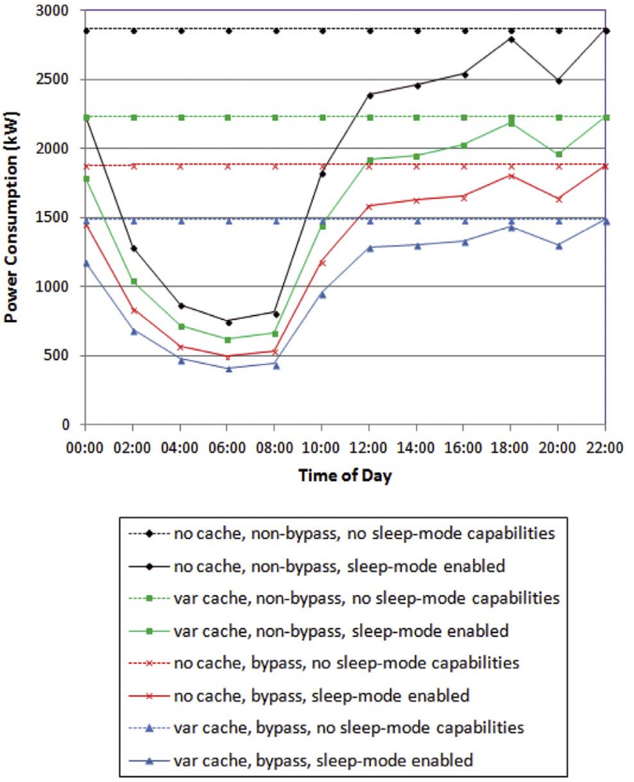

Fig. 6. Network power consumption with no caching and under variable caching considering lightpath non-bypass and lightpath bypass under current and future networks.

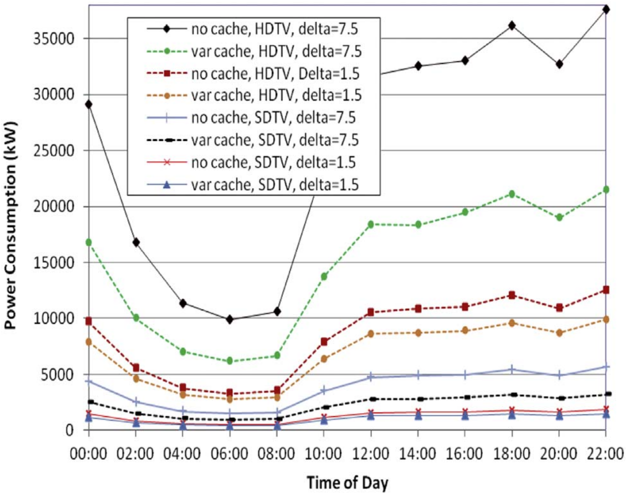

Fig. 7. Network power consumption with no caching and under variable caching considering low video demand delivered by standard definition and high video demand delivered by high definition.

Fig. 7 shows the power consumption of the network when the demand for video is low (Δ_d=1.5) delivered using SD and HD when no caches are deployed and under variable caching. It also shows the power consumption when SD and HD videos are requested at a much higher rate (Δ_d=7.5).

Observing Fig. 7, it is apparent that delivering videos using high definition streaming technologies has a greater impact on the power consumption of the network compared to increasing the volume of video demand delivered at standard definition. In other terms, improving the quality of delivered video by switching to more advanced streaming technologies has a larger impact on network traffic. Network video traffic trebles when Δ_d increases from 1.5 to 7.5. When HD is employed to deliver video, video traffic increases fivefold.

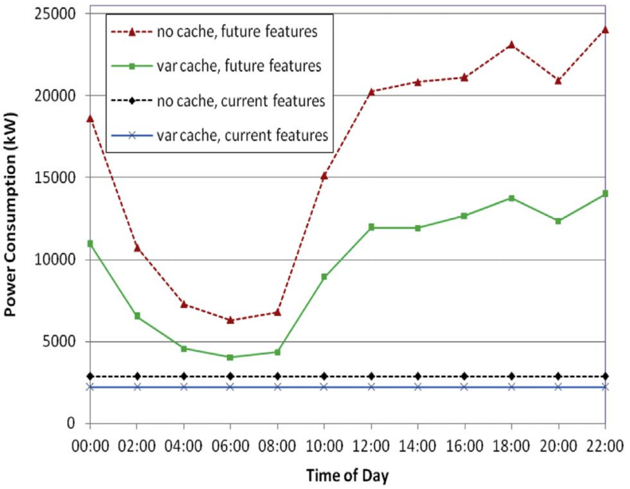

Fig. 8. Network power consumption having combined current network features (no sleep-mode capable equipment, high power consumption for network components, lightpath non-bypass and low demand for video delivered at standard definition) and combined future network features (sleep-mode capable equipment, low power consumption for network components, lightpath bypass and high demand for video delivered at high definition).

The problem of excessive power usage peaks when high demand for video is coupled with high definition streaming. Savings in power consumption due to caching are proportional to the amount of video traffic regardless of the video delivery technology. Maximum savings in power consumption are 20% when Δ_d is 1.5 considering standard and high definition videos. These savings increase to 42% when Δ_d rises to 7.5.

When the ratio of video requests remains the same, switching from standard definition to high definition results in increasing the power consumption of the network with and without the use of caching. The percentage of power saving, however, remains the same, since the cache hit ratio is constant, and therefore, the percentage of reduced video traffic due to caching is unchanged.

It can be observed that all power saving figures due to caching are similar considering different current and future network features. The similarity in these figures is explained by the fact that the evaluation takes into account a single matrix for input traffic under all considered network scenarios. This input consists of a fixed amount of download traffic throughout the power consumption evaluation. Consequently, the power savings due to caching are similar, since caching saves power as a result of reducing download traffic from data centers to nodes.

It is expected that considering a different input traffic matrix will result in different power saving figures. These figures are expected to be lower or higher based on the amount of download traffic in the traffic mixture [15]. It is also expected that the power savings in power consumption due to caching are comparable under other future network features, similar to the results in the present evaluation.

5. The combined impact

In this section we examine the influence of caching in a network environment where an optical core network is considered with all current network features implemented (no sleep-mode capable equipment, high power consumption for network components, lightpath non-bypass and low demand for video delivered at standard definition). We compare this scenario to a network implementing all future optical network features combined (sleep-mode capable equipment, low power consumption for network components, lightpath bypass and high demand for video delivered at high definition). The power consumption of the network under the two considered scenarios is shown in Fig. 8.

Table 3
Network energy consumption under different scenarios.

#	Caching option	IP over WDM implementation	Sleep-mode capable devices	Video traffic ratio	Streaming technology	Power consumption of a router port (W)	Energy consumption (MWh)
1	No cache	Non-bypass	No	1.5	SDTV	1000	68
2	Var cache	Non-bypass	No	1.5	SDTV	1000	53
3	No cache	Bypass	Yes	1.5	SDTV	1000	30
4	Var cache	Bypass	Yes	1.5	SDTV	1000	24
5	No cache	Bypass	Yes	7.5	SDTV	1000	91
6	Var cache	Bypass	Yes	7.5	SDTV	1000	53
7	No cache	Bypass	Yes	7.5	HDTV	1000	610
8	Var cache	Bypass	Yes	7.5	HDTV	1000	356
9	No cache	Bypass	Yes	7.5	HDTV	604	390
10	Var cache	Bypass	Yes	7.5	HDTV	604	231

The Internet is challenged with a great increase in the number of users and video demand. Potential improvements in optical technologies (exemplified here by sleep-mode capable devices, lightpath bypass and less power consuming network equipment) result in substantial network power reductions as specified in the previous subsections. Nevertheless, these improvements do not compensate for the expected increase in video traffic and bandwidth-consuming streaming technologies.

When comparing current optical network conditions with future optical network conditions, the overall increase in total network power consumption is a maximum of 88%. Under the current network scenario, caching saves 22% of power consumption (average of 22%). When the future network scenario is considered, caching reduces up to 43% of power consumption (average of 40%).

The magnitude of caching can be illustrated by the daily network energy consumption. Table 3 shows the energy consumption of the network under different scenarios.

From Table 3, the following are observed:

- Video caching is energy efficient under all network scenarios.
- The most influential network feature on energy consumption is the streaming technology. (scenario 7 and 8)
- When caching is employed, the increase in energy consumption due to increasing video traffic ratio is similar to the decrease in energy consumption due to implementing lightpath bypass. (scenario 2 and 6)
- Caching results in massive savings in energy consumption (up to 253 MWh per day) under HDTV. (scenario 8)
- Higher power savings due to caching are achieved when traffic peaks, supporting further growth in Internet video traffic.

6. Conclusion

This paper has evaluated the benefit of content caching in IP over WDM core networks with respect to current and future networks. It compares power savings due to caching when network devices are provisioned for peak traffic and when the network is equipped with sleep-mode capable hardware. It also evaluates the power consumption under lightpath non-bypass and lightpath bypass. Moreover, it investigates the potential of caching as a power efficient solution if the power consumption of transport significantly decreases. Finally, it evaluates the power consumption of the combined effect of all considered network features as well as daily energy consumption reductions due to caching.

The results reveal that sleep-mode capable equipment reduces a substantial amount of power due to traffic adaptation. Even though, caching introduces additional power savings of up to 38% of power consumption with and without sleep-mode capabilities. These savings increase to 42% under variable caching when sleep-mode capabilities are implemented. The results also show that when the power consumption of transport decreases, similar caching power savings of up to 42% are achieved, however, the optimum cache sizes that result in minimizing power reduce. This influence is also observed when lightpath bypass is implemented, since remote access for video content is more favorable. The power savings due to caching are up to 46% and 42% under lightpath nun-bypass and lightpath bypass, respectively. The similar power saving figure of 42% achieved under different scenarios is due to the constant input traffic used in the evaluation where caching reduces the power consumption of download traffic alone. When combining all network features, caching reduces up to 22% and 43% of power consumption under current and future optical networks, respectively. Delivering video demand using high definition technologies has a greater impact on power efficiency compared to increasing video traffic. This outcome highlights the call for developing greener video streaming technologies.

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