Optical Technologies Can Improve the Energy Efficiency of Networks

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Abstract *Optical technologies, in comparison with electronic technologies, need less power to switch high bitrates and to interconnect farther subsystems. The paper discusses with specific examples how optics can improve the energy efficiency of networks and switches.*

Introduction

Power consumption has recently emerged as a crucial problem due to increasing energy costs and to relevant environmental impacts. According to several estimates, ICT alone is responsible for a percentage from 2% to 10% of the worldwide energy consumption, and ICT emissions will almost double by 2020, reaching 1.43 Gt of CO_2 worldwide[1]. Moreover, the constant growth of the Internet traffic is continuously inducing technological advances in transmission systems and networking equipments, causing rapidly increasing power consumptions despite the efforts to build more energy-efficient devices and systems. Indeed, while the joule/bit in telecommunication networks is decreasing with time, the joule/user keeps increasing. According to several studies, current trends predict that the Internet will use 50% of the world electricity in few years.

The role of optics in reducing the energy wastage can be significant. Optical technologies emerged as the winning solution for long-distance transmissions due to the very large bandwidth and low attenuation-distance figures of optical fibers. Optical solutions are now gaining interest even in short-distance applications, such as high-performance computing, networks on chip, and routers/switches systems, in which a large number of processing units or linecards need to be interconnected to exchange large amounts of information. In this context, both the complexity and the power requirements of electronic interconnection systems do not scale well with the information density. Indeed, electronic solutions carrying higher aggregate bandwidths and operating at higher bitrates need higher wire-counts, and to impose limits to the distance that electronic signals can span without being regenerated. On the contrary, optical systems exhibit a complexity which is almost constant, or slightly increasing, with the information density and the bitrate. In particular, it is possible to achieve a communication bandwidth on a single fiber (or waveguide) of multiple terabits-per-second with limited power dissipation. In the photonic domain, power requirements are almost independent from both the bitrate and the distances covered by optical signals (they grow mainly in the transmission interface circuitry: modulators, drivers and receivers).

Reduction of power consumption was a driver even in the pioneering days when one of the first applications of optical fibers was in submarine cables, allowing to significantly reduce the number of regenerations needed by physical signals to cover the large oceanic distances. Nowadays, photonics technologies seem to be a promising solution to contain, and even to reduce, power supply and dissipation requirements in future interconnection systems needing to carry information densities that are constantly increasing.

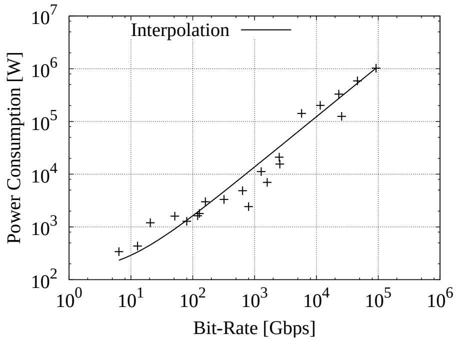

Fig. 1: Power consumption vs capacity of electronic routers.

The power consumption of current electronic devices is growing too fast with increasing traffic. As an example, Fig. 1 details the power required by different classes of routers as a function of the total switching capacity (labeled “bit-rate” in the figure). Interestingly, the power consumption is almost linear with the throughput, with top-level devices consuming today more than 10 KW of power on average. The resulting effect is that telecom operators are now responsible for 37% of global ICT emissions, while data centres and user terminals account for the remaining part[1]. In Italy, for example, Telecom Italia is the second largest consumer of electricity after the National Railway system[2]. Considering a typical Internet Service Provider (ISP), the energy consumption of the backbone network alone is more than 12 GWh in one year[3]. In this context, providing 100 Mb/s (or above) access to all citizens may be impossible due to the lack of electricity (both generation and distribution) to keep millions of electronic devices powered on.

The actual power trend characterizing the electronic technologies seems to be unsustainable; thus, moving some switching operations from the electronic to the optical domain can be a viable alternative to deeply cut down network power consumption. On the other hand, Internet was initially designed to exploit at the best the continuously improving electronic technologies, so that mimicking the current Internet operation in the optical domain is almost impossible. Hence, a deep penetration of optical technologies in routers and switches might lead to major changes in networking paradigms, offering the opportunity to re-engineer the network to better suit emerging technologies so as to enable to offer new services. For example, circuit switching appears to be more energy friendly than packet switching (note that optical and digital cross-connects –OXC and DXC– need less power than packet switches).

Networking applications of optics

The attention of the scientific community towards energy efficiency in networking has rapidly increased. Several workshops at major international conferences, but also dedicated conferences, were recently organized on "green networking". Several international research programs recently focused on power saving issues; for example, the BONE FP7 Network of Excellence on optical networks recently started a new workpackage dedicated to these issues.

Different solutions can be considered to achieve energy savings in optical networks. For example, in[3] we consider a **network-level approach.** The basic idea is to turn off some elements (nodes and links) under connectivity and Quality of Service (QoS) constraints, given a network topology and a traffic demand as inputs. In particular, the goal is to minimize the total power consumption of a realistic ISP network, by exploiting the traffic variability that is often observed. In[3] we considered the traffic profile measured at a peering node, in which off-peak traffic is nearly 40% of the peak traffic demand, and less than 80% for more than 12 hours, so that the total effect on the network is a low resource utilization during night periods. By exploiting the traffic dynamics, large amounts of devices can be powered off, still guaranteeing that the resource utilization remains below a given threshold. e.g., 50%. Results show that 50% of nodes and 30% of links can be powered off in off-peak periods, saving 23% of energy.

This entails shifting the network design and control criteria from the traditional approach of evenly spreading traffic on all available resources to minimize congestion, to concentrating traffic to the minimal subset of resources that can guarantee service delivery at the desired quality level to save power.

Energy-efficiency can be introduced also in the design of both the access and the core network segments. Nowadays, all around the world, several Internet providers are actually providing to their users the opportunity to switch from the standard xDSL or cable TV access to optical fiber access. For instance, to deliver high speed Internet, video and voice to its final users, Verizon is already offering all-fiber optic broadband access, ensuring a connection speed up to 50 Mbps full duplex (upgrades up to 100 Mbps have already been considered). Indeed, **Passive Optical Networks** (PONs) are designed to provide higher bandwidth to final users than the older access technologies without employing any active elements along the signal path; thus, leading to a strong reduction in power consumption and operational expenditure. Several studies show that, among access systems, PONs provide most capacity at the best total cost of ownership (TCO).

Regarding the core segment, **Wavelength Routing** (WR) networks offer the flexibility of designing a "logical topology", comprising lightpath requests, over a physical topology, comprising OXCs and links with many fibers each. The Routing and Wavelength Assignment (RWA) problem is well known in the literature: its goal is to assign a route and a suitable wavelength in the physical topology for each lightpath of the logical topology. Traditionally, the solutions obtained from the RWA problem lead in general to a waste in the power required to keep up and running both OXCs and optical amplifiers along fiber links. In[4] we targeted the minimization of power consumption when solving the RWA problem, by making maximum usage of powered-on devices, e.g., by reusing the same fiber along the same path as much as possible, in contrast to spreading lightpaths on available fibers and paths. Simulation results show that a significant amount of power can be saved, reducing up to 5 times the energy needed to operate a WR network.

Optical technologies are making their own way from long distance transmissions to short range transmissions. Power constraints due to packaging and power budget limitations are among the most limiting factors in **Network on Chip** (NoC) systems, in which networks are used to provide connectivity among several processing units (either cores or CPUs depending if we are considering "On Chip" or "Chip to Chip" scenario). As such, in current prototypes with tens of cores the power dissipated by the electronic NoC accounts for over 25% of the overall power and the power of a NoC implemented with current circuit techniques is estimated to be too high (by a factor of 10) to meet the expected needs of future multicore systems. In this context, photonic technologies promise to provide a mechanism for both intra-chip and inter-chip large data transfers with minimal power dissipation. A tenfold reduction of the power dissipated by data transfers in a multi-core chip is reported in[5] when a large FFT is computed.

The growth of the Internet traffic, well supported at the transmission level by the huge amount of bandwidth available through optical fibers employing Wavelength Division Multiplexing techniques, is driving the evolution of new generation of routers and switches. Currently, high-end routers and switches are based on electronic technologies that are actually reaching their physical limits. Some researchers even start questioning the validity of Moore's law (which predicts a doubling of performance very 18 months) in the near future. Indeed, each new router generation requires more complex control algorithms and consumes more power than the previous one. In this context, the reduction of routers' and switches' power consumption imposes to move some switching operations directly into the optical domain; thus, requiring new architectural solutions because the lack of optical memories and the limited processing capabilities of optics makes it difficult to solve conflicts in time domain through dynamic operations, as required by the packet switching paradigm based on electronic technologies[6].

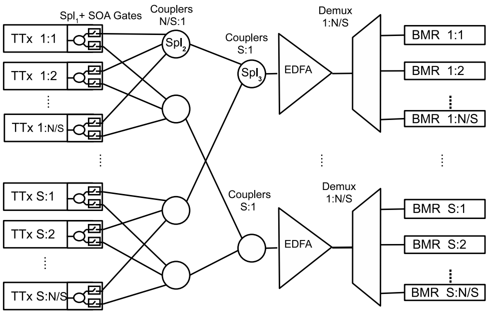

Fig. 2: Multiplane Couple-Amplify-Demultiplex (MCAD) architecture.

Power scaling of optical switching fabrics

A very interesting area of application of optical technologies, upon which both academia and industry recently focused, is the realization of optical switching fabrics and interconnection systems.

In this section we refer to a high-performance packet switch, with linecards where packets are processed and stored to solve contentions in the electronic domain. These linecards are interconnected by an optical switching fabric. Externally the switch is fully compliant with existing protocols and data formats. In[7,8] our research group assessed the scalability and cost of some simple all-optical switching fabrics based on the "Tunable Transmitters (TTx) - Fixed receivers (FRx)" paradigm. Differently from many works appeared in literature, the architectures considered in[7,8] exploit only off-the-shelf components; packet switching is controlled at each input linecard by means of a fast tunable laser (i.e., in the wavelength domain) and, possibly, by a fast optical switch (i.e., in the space domain). Each linecard is equipped with one tunable transmitter (TTx) and one fixed wavelength burst mode receiver (BMR) operating at the data rate of a single WDM channel. The interconnection architectures are synchronous, time-slotted, and packet transmissions are scheduled so that at most one packet is sent to each receiver on a time slot (i.e., contentions are solved at transmitters).

In[8] the concept of switching plane is introduced to reduce the number of wavelengths each transmitter is required to tune to: a tradeoff between wavelength and space multiplexing permits to control the laser tuning range, which can be a critical technological parameter. As an example, we describe here the Multiplane Couple-Amplify-Demultiplex (MCAD), which is depicted in Fig. 2. The plane selection stage is built with Optical Semiconductor Amplifiers (SOA) used as on-off gates. Other two optical fabric architectures were studied in[8], dubbed Wavelength-Selective "V" (WSV) and Wavelength-Routing-Space (WRS). The former is based on SOA gates, the second on Arrayed Waveguide Gratings (AWGs), and come into variants: WRS and WRS-zc. All these architectures show a common EDFA-amplification and receiving stage, but we omit further details for space limitations.

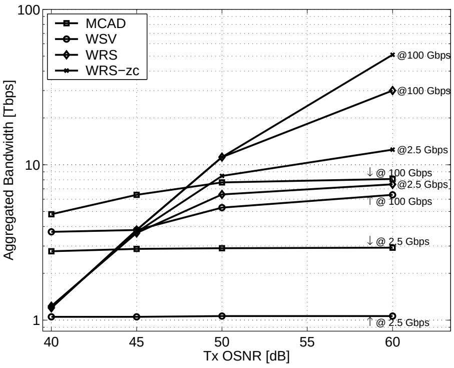

Fig. 3: Aggregate bandwidth as a function of the transmitter noise $OSNR_{TX}$.

The considered optical fabrics did not include any signal regeneration but only pure linear optical amplification. In[7,8], datasheets-based models of the different components were proposed, capable of capturing several important physical effects as insertion losses, excess losses, channel uniformity, polarization dependency and crosstalk. These effects were translated into power penalties and then related to port and plane counts. The scalability of the different optical fabric was then assessed in number of ports and planes varying the linecard bitrate. For the receiver, it was required a signal to noise ratio of 17 dB, defined over a bandwidth equal to the bitrate, to guarantee a target BER of 10^{-12}. Furthermore, to ensure such value of BER, best receivers at 10 Gbps have today a typical receiver sensitivity around -26 dBm. To address scalability at different bitrates, a sensitivity slope vs. bitrate of 13.5 dB/decade was assumed; thus, for instance, -17.8 dBm is the sensitivity of a burst mode receiver operating at 40 Gb/s.

Fig. 3 shows for the different fabric architectures the maximum achievable capacity as a function of the noise level at transmitters, which is a dominant performance parameter. We see that by imposing realistic sensitivity and signal to noise ratio constraints at receivers ensures that optical switching fabrics based on components which are commercially available today achieve aggregate bandwidths of several Tb/s; our study shows that their scalability is mainly limited by in-band crosstalk due to transmitter noise accumulation at the receivers.

For the optical switching fabrics above, it is interesting to estimate the power consumption and to compare it, both in absolute values and in scaling trends, with the power consumption of equivalent electronic subsystems. Fig. 4 shows a logical block diagram of the components considered in the power evaluation of the MCAD architecture. Based on datasheets of commercially available devices, we inferred a power model for each of these components as a function of the bitrate. The logical diagrams of the other architectures and the device models are not reported here due to space limitations. Figs. 5–7 show the total power consumption as a function of the bitrate for the MCAD, the WSV,

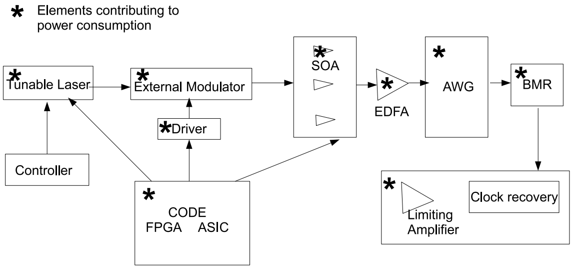

Fig. 4: Block diagram showing the components considered to estimate the power consumption of the MCAD architecture.

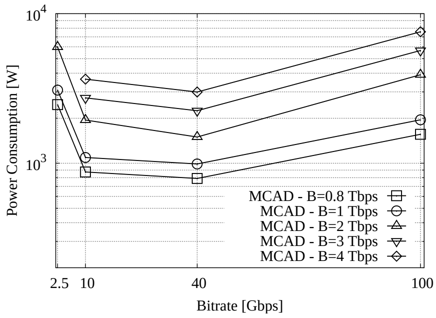

Fig. 5: Power consumption of the MCAD architecture.

and the WRS architectures. For each particular optical fabric, several values of the aggregate bandwidth were considered. The behaviour of the power consumption strongly depends on the bitrate, hence on the technology used, whereas it is mostly independent from the switching fabric architecture. Indeed, lower bitrate (for instance 2.5 Gbps) are based technologies which can be now considered consolidated and almost obsolete, whereas, highest bitrates (as 100 Gbps) require technologies which are not mature yet. The minimum power consumption occurs using available and mature technologies.

Fig. 8 compares the power consumption of the MCAD architecture and the power consumption of the CRS-1 Cisco router, which is one of the largest packet switching devices offered on the market today. Trying to be fair in the comparison, we considered only the power needed by the CRS-1 switching fabric cards, which are declared to contribute for the 15% of the whole router power consumption. In the range of the considered aggregate bandwidths (the ones achievable under receiver sensitivity and signal-to-noise ratio constraints), the MCAD optical fabric presents a lower power consumption than the electronic fabric, and to scale better. Note that this gain is expected to be much higher moving from architectures based on discrete components (as we considered in this paper) to integrated designs and properly engineered implementations.

Conclusions

In this paper we argued that power saving can be the driver for a deeper penetration of optical technologies in networking beyond point-to-point transmission. We provided examples of how optics can be exploited in switching, and discussed with some detail the power consumption of optical switching fabrics to be used inside large packet switches.

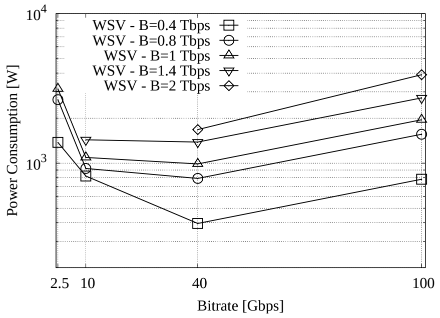

Fig. 6: Power consumption of the WSV architecture.

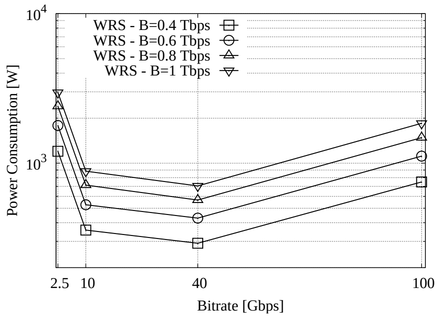

Fig. 7: Power consumption of the WRS architecture.

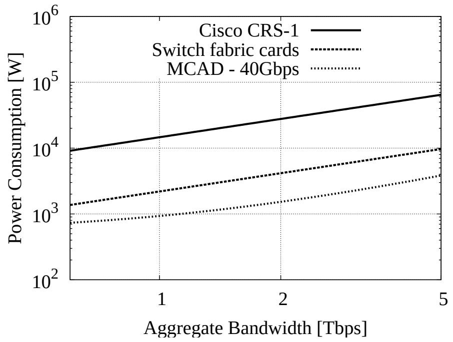

Fig. 8: Comparison between the power consumption of the MCAD architecture and of the Cisco CRS-1 router.

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