Green ICT for Sustainability: A Holistic Approach

(invited)

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Abstract – In the last three decades, the information and communication technology (ICT) sector has been growing very fast. There is no such example in human history that development of a technology has changed our way of life in such a rapid and fundamental manner. ICT has become an integral part of our everyday life including social interactions, business processes, technology and ecology. Due to the fact that ICT not only promises enormous potentials but also carries risks, it is extremely important to carefully evaluate and assess ICT systems and applications regarding their potential for improving the global energy productivity in a sustainable manner.

This paper concentrates on technologies and methods for achieving high-performance and energy-efficient communication networks. Main achievements and trends towards highly energy-efficient network infrastructure are briefly reviewed. A novel holistic framework able to efficiently treat energy, entropy, and exergy flows in heterogeneous systems through combining thermodynamic and communication approaches is presented.

I. Introduction

Although information and communication technology (ICT) has been making an enormous progress for more than thirty years and has already influenced many areas of our everyday life, its potential benefits and risks for the environment have gained the interest of the scientific research and broad community only since recently. Even though many extensive studies on energy efficiency of ICT systems have been carried out during the last several years, the influence of ICT on the environment has still not been sufficiently assessed and understood.

On the one hand, broad and intensive use of advanced ICT applications and services promises substantial improvements in many branches such as in industry, logistics, trade, healthcare, and education as well as in society. Furthermore, ICT applications can be used to optimize various processes and, consequently, to support new strategies and mechanisms for a sustainable exploitation of natural resources.

On the other hand, the ever increasing number of ICT equipment and intensive usage of ICT services lead to a continuous increase of ICT-related energy consumption. Additionally, the short lifetime of devices and services cause an increased usage of resources, production intensification, and more hazardous e-waste, which can harm the environment.

The aim of this paper is to briefly summarize recent progress in analyzing communication networks from the energy efficiency perspective and to discuss possibilities of developing and applying a holistic approach in assessing and studying environmental sustainability of different network concepts and ICT applications.

The rest of the paper is structured as follows. The next section summarizes the main trends and projections regarding communication networks, data centers and high-performance computers with particular emphasis on energy consumption. In Section III, we address the methods proposed so far to reduce energy consumption and increase energy efficiency of network infrastructures. Section IV discusses different metrics for energy efficiency. A holistic approach for analyzing sustainability of networks is briefly presented and discussed in section V. Finally, Section VI summarizes and concludes the paper.

II. Recent Trends in Communication Networks with Particular Emphasis on Energy Efficiency

The significance of considering energy consumption when developing new technologies and concepts for future networks becomes evident when observing the current situation and projections for the next five to ten years. Already in 2007, the ICT carbon footprint has been estimated to count for about 2 % of the total carbon emissions worldwide, which is comparable to the carbon footprint of the aviation sector [1]. At that time, the estimated ICT-related electricity consumption was above 17 TWh, which corresponds to the production volume of 15 medium-scale nuclear power plants. In 2020, the contribution of the ICT sector to the global carbon emissions is expected to increase to above 4 % [2]. It is worth noting that about 51 % of the ICT-related energy consumption is used by telecommunication infrastructure and data centers. However, it has been estimated that ICT-enabled solutions offer the potential to reduce overall annual emissions by 14.2 % of the projected total in 2020 [2]. According to a more recent estimation, this potential has been revised to 16.5 % [3]. Hence, both the ICT-related energy consumption and the abatement potential grow with time and it is not yet clear if ICT will rather become an important environment pollution source or an enabler for a more efficient and ecological resource management.

A. Increasing Bandwidth Demand

The continuous growth of Internet traffic has led to rapidly increasing capacity provided by network infrastructure. Observations have shown that the main contributor to the traffic increase in the Internet is the traffic from residential customers [4]. This is mostly because of introduction of new bandwidth-hungry applications for residential users but also due to the fast growth of the number of broadband subscribers [5] as it is evident from Fig. 1.

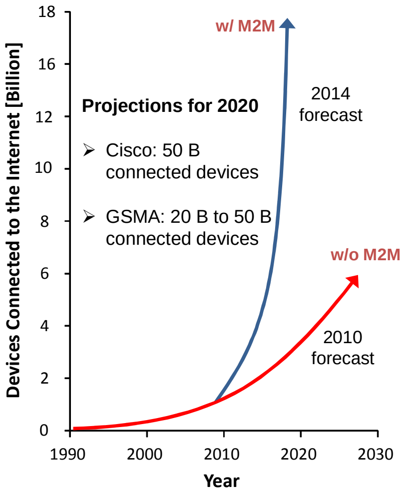

Figure 1. Recent trends in number of devices connected to the Internet [6]. M2M: Machine-to-Machine Communication.

Due to the concurrent growth of Internet traffic and the number of subscribers, both the number of network elements and their capacity are also expected to increase in the future. Recent introduction and wide penetration of smartphones and tablets confirm this trend. Furthermore, according to the vision of the “Internet of Things”, it is expected that in the foreseeable future, a huge number of smart autonomous devices will communicate via the Internet, which is referred to as Machine-to-Machine (M2M) communication. As indicated in Fig. 1, it is projected that 50 Billion of smart autonomous devices will be connected to the Internet in 2020 [4]. For this reason, energy efficiency of both network and end-user equipment has become a very important issue.

Historical development and some projections for future trends concerning the growth of Internet traffic and the increase in router capacity and line data rate are presented in Fig. 2. In the past, user traffic was increasing by about 100 % per year. Within the last few years, this growth has slowed somewhat, so that the traffic volume in global communication networks is currently increasing by approximately 50 % per year [7]. In order to keep track with this increasing demand for bandwidth, the capacity of underlying network components has to increase too. However, when considering IP routers, the capacity per rack of equipment has been increasing with a lower rate than Internet traffic. As can be seen from Fig. 2, the capacity per rack was increasing by about 75 % per year for more than ten years. The increase in capacity has slowed in the last few years, which is mostly due to increased energy density and limited cooling rate. The increase of port (line) data rate has been also slowed down to some extent in the last several years. While in the past line data rate increased by a factor of four each three years or by a factor of ten per approximately six years, the step from 40 Gbit/s to 100 Gbit/s, which corresponds to an increase by a factor of 2.5, took more than three years. In order to keep the same increasing rate as during the last decade, the next generation optical transceivers operating at the line data rate of 1 Tbit/s should be already available.

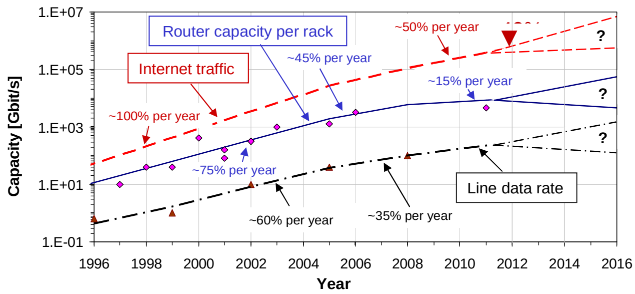

Figure 2. Recent trends in Internet traffic and router capacity [8].

Fig. 3a shows the estimated total power consumption of electronic routers for capacities up to 100 Tbit/s with some examples of electronic high-performance routers represented by the blue dots in Fig. 3a [9]. According to this figure, the router’s power consumption increases linearly with bandwidth and each new generation of high-capacity electronic routers consumes more power than the previous one.

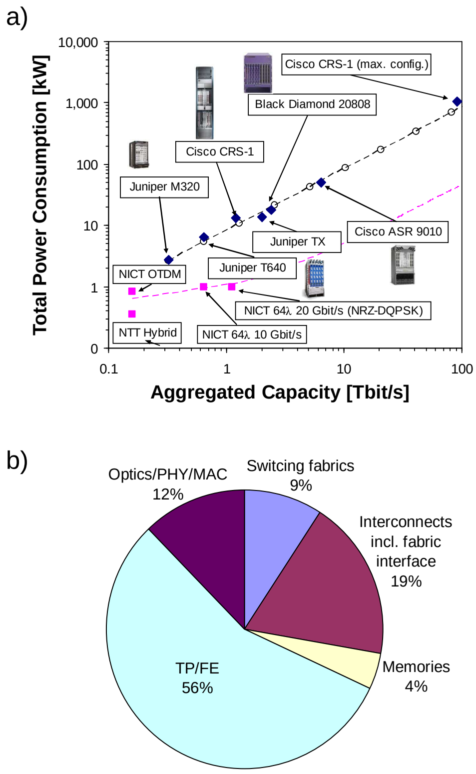

Figure 3. Power consumption of switches and routers [9]. MAC: Medium Access Control, PHY: Physical Layer Chip, TP: Traffic Processing, FE: Forwarding Engine.

About 60 % of the total power consumed by a router is related to IP traffic processing (see Fig. 3b – TP/FE and

Memories). Thus, the most potential for reducing the high power consumption of routers lies in simplifying the network concept in order to reduce the need for the complex and power hungry switching and processing at the packet level. A few examples of optically switched routers are also presented in Fig. 3a by the magenta dots and the corresponding dashed line. It should be noted here that data processing and storage elements realized using current optical technology usually have a quite limited complexity. Consequently, achievable performance of the optically switched routers is not as high as that of their electronic counterparts. Accordingly, the power consumption of an optical router is considerably lower than that of an electronic router assuming the same capacity.

B. Data Centers and Cloud Computing

Data center traffic has been showing an exponential increase mainly due to the introduction of emerging cloud computing applications. It has been estimated that for every byte of user data transmitted over the Internet, 1 GByte are transmitted within or between data centers [10]. While the amount of data-center traffic crossing the Internet is projected to reach 1.3 zettabytes per year in 2016, the amount of traffic within data centers has already reached 1.8 zettabytes per year [11], and by 2016 will grow by a factor of 3.6 to about 6.6 zettabytes per year. This corresponds to a compound annual growth rate (CAGR) of 31 % from 2011 to 2016. The key driver to this growth is cloud computing traffic that is expected to increase six-fold by 2016, becoming nearly two-thirds of the total data center traffic.

Another issue rising with the increase in the data center traffic is energy consumption. The direct electricity used by data centers has shown a rapid increase in the last years. The worldwide electricity use in data centers doubled from 2000 to 2005 and, from 2005 to 2010, it increased by about 56 % [12,13]. It has been estimated that data centers accounted for 1.3 % of the worldwide electricity use in 2010, being an important contributor to the worldwide energy consumption.

C. High-Performance Computing

Similar trends can be observed for large data centers and high-performance computers. Some examples of recently developed systems and projections for power consumption of high-performance computers (HPCs) are shown in Fig. 4. The red dots represent a selection of currently existing HPC systems, of which two illustrative examples are named. It is evident form Fig. 4b that already today large HPC systems consume several MW of electricity [14]. Future Exascale computer systems will probably consume more than 20 MW, which will set very high requirements on power supply and cooling systems. Therefore, a large effort has to be put into research and development of more energy efficient structures and technologies in order to make possible further scaling in both capacity and performance.

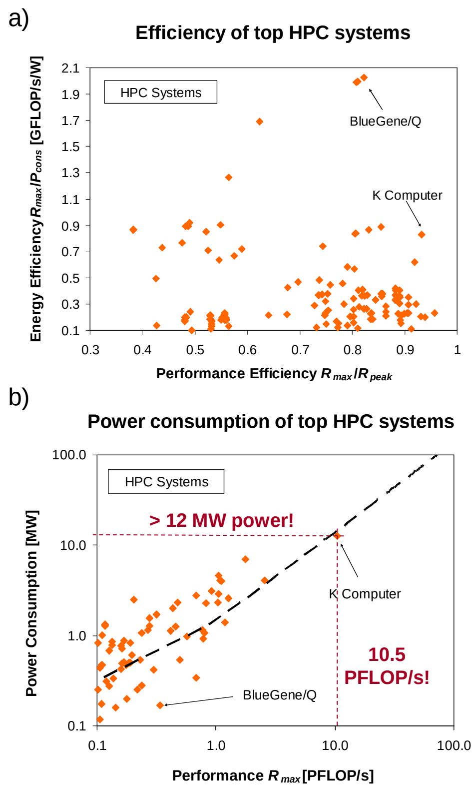

Figure 4. Recent trends in high-performance computing (HPC). Data taken from [14].

III. Methods for Improving Energy Efficiency of Communication Networks

It is widely recognized that future network elements must be able to provide high performance while featuring reduced power consumption. These high requirements can only be satisfied through a combined effort of research community, network designers, and network operators. Such an ambitious goal can be attained by developing and applying energy-efficient data transmission and processing systems, adaptive transmission links, dynamic power management and dynamically switching off or putting in sleep mode transmission links and line cards that are less utilized [15-19]. It has been shown that significant savings in energy consumed by network infrastructure can be achieved when optimizing both the network concept and the architecture of network elements with regard to energy consumption. Energy-efficient switching technologies and paradigms, power-aware routing and wavelength assignment (RWA) algorithms as well as multilevel traffic engineering and cross-layer optimization are examples of methods that can be applied at system level.

IV. Metrics for Energy Efficiency

There have been a number of metrics proposed and used to assess and compare communication systems and networks with respect to achievable reduction in energy consumption and energy efficiency. Some of mostly used metrics are listed in Table I. The most simple and intuitive metric seems to be absolute power consumption. However, absolute power consumption is not a measure of efficiency because it says nothing about how useful the system actually is. Similarly, power consumption per subscriber, per area or even per bit of capacity does not consider the actual usage of the system. All these metrics presume a utilization of 100 %. Differently, energy consumed per bit of throughput considers the system performance and is therefore suitable for comparison purposes, but it still gives no idea of what would be theoretically possible, i.e., there is no relation to theoretical minimum energy dissipation.

TABLE I. ENERGY EFFICIENCY METRICS

Definition	Unit	Comment
Power consumption	[W]	no relation to usage at all
Power consumption per subscriber	[W/subscriber]	no relation to usage at all
Power consumption per area	[W/km^2]	no relation to usage at all
Power consumption per subscriber and area	[W/subscriber/km^2]	no relation to usage at all
Energy consumption per bit of capacity	[W/bit/sec ≡ J/sec]	no relation to usage at all
Energy consumption per bit of throughput	[W/bit/sec ≡ J/sec]	no relation to theoretical limit
EEF=10log$_{10}$[Energy/bit/($k_B T$ln2)]	[dBε]	inverse to efficiency

The recently proposed metric referred to as energy efficiency figure (EEF) [20] takes into account the theoretical minimum energy required to process one bit of information that can be calculated using the formula $k_B T$ln2 [21], where k_B is the Bolzmann constant and T is the absolute temperature. This theoretical limit can be used to compare heterogeneous systems and to indicate the theoretically possible improvements. However, EEF is, similarly to all other metrics listed in Table I, an inverse efficiency metrics. That means the higher its value the lower energy efficiency.

V. HOLISTIC APPROACH TO SUSTAINABLE NETWORKS

The overall impact of ICT on environment can be classified into direct, indirect and systemic effects [8, 22-24]. The direct effects comprise environmental impacts related directly to the life cycle of ICT infrastructure, including the production, use, recycling and disposal of ICT. The indirect impacts refer to environmental impacts that result from the use of software applications and ICT services that can lead to energy savings in other areas. Finally, the systemic impacts relate to environmental impacts that emerge from the medium or long-term changes of behavior and economic structures following from the availability of ICT applications and services and include all non-technological factors such as adjustment of individual lifestyles and rebound effects.

A study of the direct impacts should preferably include the whole lifecycle of the telecommunication network infrastructure and user devices. However, as briefly addressed in Section III, most of the studies accomplished so far concentrated on reducing the energy consumed during the operational (use) phase only [8,9,15,23,25].

Direct, indirect and systemic impacts can only be considered when applying a holistic approach such as the one illustrated in Fig. 5 [8]. The holistic approach presented here makes use of widely used thermodynamic tools to indicate and model energy and entropy flows within heterogeneous subsystems and through the boundaries between the systems, while taking into consideration peculiarities of each system. In particular, the potential of ICT applications and services can be evaluated and accessed by means of possible improvements of energy efficiency. The influence of the global communication network (the Internet) on the global energy productivity, environment and sustainable development can then be estimated by taking into account direct, indirect and systemic effects.

A. *Model of Communication Networks*

A model of communication networks representing the central part of the global system model as illustrated in Fig. 5 should take into account not only technological aspects and different realization options, but also social, economic, and demographic peculiarities as well as possible future developments. Such a model could

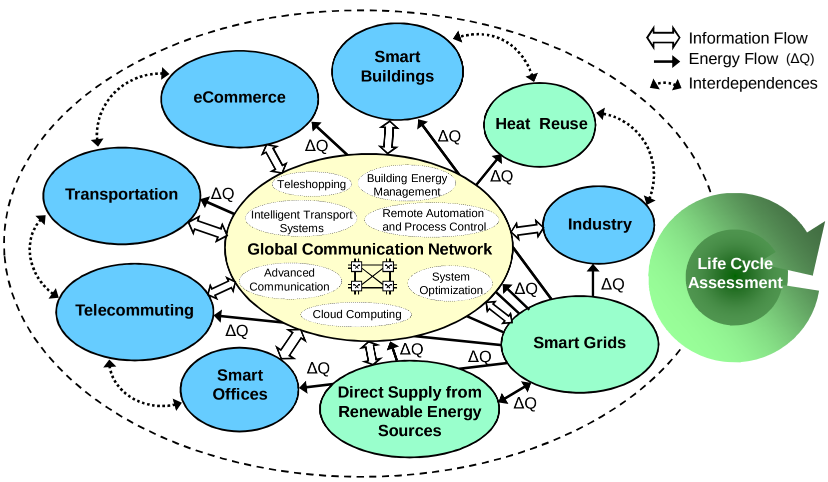

Figure 5. High-level illustration of the global system including the global communication network, applications and other subsystems that can make use of the global network infrastructure in order to improve the global energy productivity. The figure also shows information and energy flows as well as interdependencies within the global system.

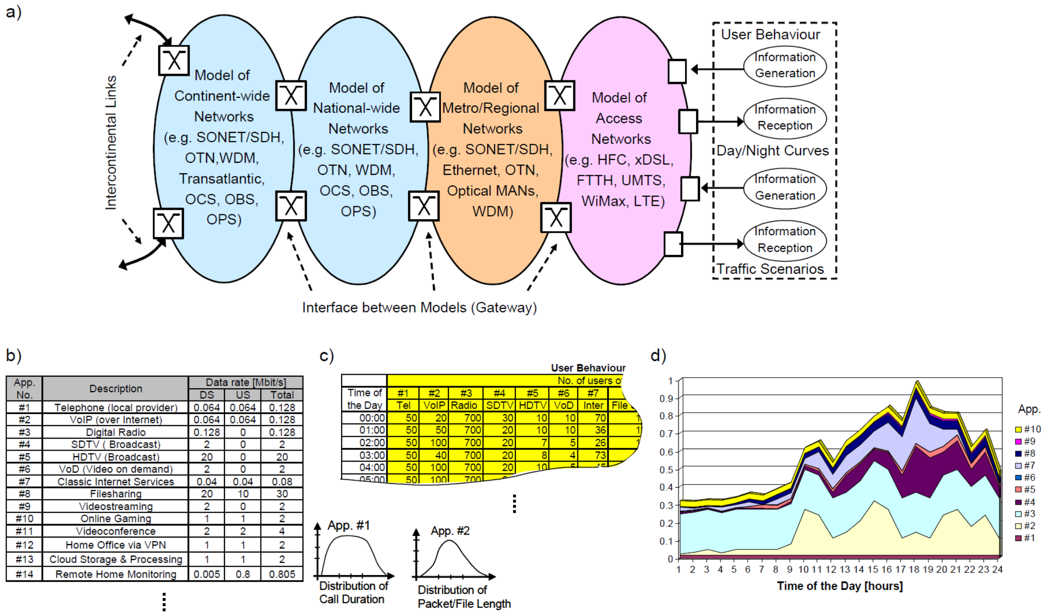

Figure 6. Hierarchical approach to model performance and energy efficiency of the global communication network; b), c) and d) hypothetical examples of applications characteristics and user behavior: b) applications' characteristics, c) user behavior respective application use and c) an example presenting application-specific traffic over the day.

comprise a number of sub-models needed to study different network areas and technologies in a detailed manner, whilst the overall picture can be obtained by joining the individual sub-models together into a global hierarchical model with a manageable complexity. For this purpose, the global communication network can be divided into different areas based on geographical, technological, and operational aspects. For each network area, a different simulation model can be developed, which considers all peculiarities of the particular area such as suitable network technologies, topologies, configuration parameters and realistic traffic scenarios (see Fig. 6).

The sub-models can be connected to each other in a hierarchical manner, where the lowest hierarchy represents the network segment close to the traffic generators (i.e., end users' equipment) and the highest hierarchical level are high-capacity long-haul transmission links that interconnect continental-wide networks (i.e., intercontinental links). Presumably, the most logical way to divide the model of the global communication network into sub-models is to follow the network area principle, namely to model separately local, metropolitan, regional, national-wide, and continent-wide networks. For each of the sub-models we can consider different network concepts and transmission technologies as depicted in Fig. 6a. Statistical data on population, ICT applications and services as well as a model of user behavior can be used to set parameters of traffic generators. An illustrative example of how to define the traffic patterns is shown in Figs. 6b, 6c and 6d, in which the main characteristics of various applications such as average data rate, maximum data rate and appropriate distribution functions as well as average usage of each application over the day are taken into account. In this way, we can study the influence of new applications and include user behavior in order to define different scenarios for possible future developments. The interface between two sub-models, i.e., between two hierarchical levels, is defined by the amount and characteristics of the aggregated traffic sent/received by the gateway interconnecting these two network areas. The following steps can be made when developing a sub-model:

- First, network nodes are modeled by taking into account technological and architectural aspects.
- Then, the network sub-models are developed under consideration of different concepts, topologies, communication protocols, and traffic scenarios.
- The total power consumption of a sub-model is calculated using realistic values for each functional block and according to the actual utilization of network elements.
- Finally, the flow of information and energy through the entire global communication network can be identified and evaluated by defining and implementing the interfaces between the sub-models.

B. *Exergy-based Life Cycle Assessment*

In order to build a holistic framework, the model of communication networks briefly presented in the previous section can be extended by integrating some widely applicable tools of thermodynamics. A very useful quantity that stems from the second law of thermodynamics is exergy. It can be used to clearly indicate inefficiencies of a process by locating the degradation of energy. In its essence, exergy is the energy that is available to be used, i.e., the portion of energy that can be converted into useful work. Exergy analysis has been performed in industrial ecology to indicate the potentials for improving resource utilization and minimizing environmental impacts. The higher exergy efficiency is, i.e., the lower exergy losses, the better the sustainability of the considered system or approach.

Life cycle assessment (LCA) is a technique to evaluate environmental impacts of a product or a process over its entire life cycle (i.e., raw material extraction, manufacture, transportation, operational, maintenance, and recycling phases). LCA analysis provides a system perspective across the whole life time to define the system boundaries and aid decision making for system optimization and product selection. The approach that combines the exergy concept with the LCA analysis is referred to as exergy-based LCA (E-LCA). Since exergy-based analysis is a universally applicable method to assess process efficiency, it is well suited to investigate the sustainability of heterogeneous systems [27-29]. Recently, E-LCA has also been used to assess the sustainability of ICT infrastructure and applications [30-33]. The preliminary results of these studies have indicated the importance of a sustainable technological development able to ensure both high rate of innovations and increased service lifetime of ICT devices. Even though a fast technological development can lead to both the high performance and high energy efficiency of ICT equipment, the sustainability of the overall system is strongly influenced by short service lifetime of user devices, which causes a considerable increase in the total embodied exergy and thus high environmental impacts.

VI. Conclusions

Recent and future trends in the information and communication technology (ICT) sector and in particular in technologies and applications for communication networks indicate an urgent need for a significant improvement in energy efficiency. Since ICT has become an integrated part of our business and everyday life, the complex interdependences between ICT on one side and various areas of business and society that make use of ICT on the other can only be appropriately treated using a holistic approach. Such a holistic approach for analyzing heterogeneous systems has been briefly presented in this paper. It combines thermodynamic and communication approaches in a life cycle framework in order to assess the environmental sustainability of ICT technologies as a part of the global system.

References

[1] The Central Intelligence Agency „The World Factbook!", Available online: https://www.cia.gov/library/publications/the-world-factbook.

[2] The Climate Group, „GeSI report - Smart 2020: Enabling the low carbon economy in the information age", 2008.

[3] The Climate Group, „GeSI SMARTer 2020: The Role of ICT in Driving a Sustainable Future", December 2012.

[4] Cisco Visual Networking Index, „Global Mobile Data Traffic Forecast Update, 2013–2018", 2014.

[5] D. Evans, „The Internet of Everything", Cisco IBSG, 2012.

[6] S. Aleksic, G. Franzl, Th. Bogner, O. Mair am Tinkhof, „Energy-Efficient Internet Access", 2nd RESPONDER Workshop on Green ICT for Sustainable Consumption, Vienna, January, 2013.

[7] C. Lange D. Kosiankowski, C. Gerlach, F.-J. Westphal, A. Gladisch, „Energy consumption of telecommunicationnetworks", In ECOC 2009, Vienna, Austria, Sept. 20–24. Paper 5.5.3.

[8] S. Aleksic, „Energy-Efficient Communication Networks for Improved Global Energy Productivity", Telecommunication Systems, Vol. 54, No. 2 , 2013, pp. 183-199.

[9] S. Aleksic, „Analysis of Power Consumption in Future High-Capacity Network Nodes", IEEE/OSA Journal of Optical Communications and Networking, 2009.

[10] G. Astfalk, „Why optical data communications and why now? " Applied Physics A, Vol. 95, 2009, pp. 933-940.

[11] Cisco white paper: '„Cisco Global Cloud Index: Forecast and Methodology, 2011-2016", 2012.

[12] J. Koomey, „Worldwide electricity used in data centers", Environmental Research Letters, Vol. 3, No. 034008, 2008.

[13] J. Koomey, „Growth in Data Center Electricity use 2005 to 2010" The New York Times, Vol. 49, No. 3, 2011 pages 24.

[14] TOP500, Available online: http://www.top500.org.

[15] S. Aleksic, „Energy efficiency of electronic and optical network elements" (invited) IEEE J. Sel. Top. Quantum Electron. 2011, Vol. 17, pp. 296–308.

[16] A. Tzanakaki, K. Katrinis, T. Politi, A. Stavdas, M. Pikavet, P. van Daele, D. Simeonidou, M. J. O' Mahony, S. Aleksic, L. Wosinska, P. Monti, „Dimensioning the future pan-european optical network with energy efficiency considerations" IEEE/OSA JOCN 2011, Vol. 3, pp. 272–280.

[17] S. Aleksic „Power consumption issues in future high-performance switches and routers" (invited), Proc. of ICTON, June 22-26, 2008, Athens, Greece, pp. 194–198.

[18] W. Van Heddeghem, M. Deruyck, B. Puype, B. Lannoo, W. Joseph, D. Colle, L. Martens, P. Demeester, „Power consumption in telecommunication networks: Overview and reduction strategies", IEEE Comm. Mag., 2011, Vol. 49, pp. 62–69.

[19] M. Fiorani, M. Casoni, S. Aleksic, „Performance and power consumption analysis of a hybrid optical core node", IEEE/OSA JOCN, Vol. 3, 2011 pp. 502–513.

[20] M. C. Parker, S. D. Walker, „Roadmapping ICT: An Absolute Energy Efficiency Metric", IEEE/OSA JOCN, Vol. 3(8), 2011.

[21] R. Landauer, „Minimum energy requirements in communication" Science 1996, Vol. 272, pp. 1914 - 1918.

[22] OECF, „Greener and smarter: ICTs, the environment and climate change" Paris 2010.

[23] L. M. Hilty, V. Coroama, M. O. de Eicker, T. F. Ruddy, E. Müller, „The Role of ICT in Energy Consumption and Energy Efficiency", Scientific Survey (WP8), Project ICT-ENSURE: European ICT Environmental Sustainability Research, 2009.

[24] K. Dobernig, I. Røpke, M. Grubbe, and M. Blum, „Green ICT for Growth and Sustainability?", Background Paper to the 1st Multinational Knowledge Brokerage Event, RESPONDER, Vienna, Austria, 30 May – 1 June, 2012,.

[25] D. Simeonidou, M. Pickavet (Editors), D21.3: „Final TP report on Green Optical Networking", Project BONE, EU FP7, ICT, 2011.

[26] S. Aleksic, „Energy and Entropy Flow in Erbium Doped Fiber Amplifiers: A Thermodynamic Approach", IEEE/OSA Journal of Lightwave Communications, Vol. 30, No. 17, June 2012, pp. 1-7.

[27] T. Gutowski, J. Dahmus, A. Thiriez, M. Branham, A. Jones, „A Thermodynamic Characterization of Manufacturing Processes", Proc. of the IEEE International Symposium on Electronics and the Environment, Orlando, FL, USA, 7–10 May, 2007; pp. 1–6.

[28] A. Masini, R. U. Ayres, „An Application of Exergy Accounting to Four Basic Metal Industries", CMER, INSEAD, Fontainebleau, France, 1996, pp. 1–51.

[29] M. A. Rosen, C. A. Bulucea, „Using exergy to understand and improve the efficiency of electrical power technologies", Entropy 2009, Vol. 11, pp. 820–835.

[30] C. R. Hannemann, V. P. Carey, A. J. Shah, „Lifetime Exergy Consumption as a Sustainability Metric for Enterprise Servers", Proc. of ASME Int. Conference on Energy Sustainability, Jacksonville, FL, USA, Aug 10-14, 2008, ASME ES2008-54181.

[31] S. Aleksic, M. Safaei, „Exergy based analysis of radio access networks" (invited), Proceedings of ICEAA - IEEE APWC - EMS 2013, 2013 pp.1–8.

[32] S. Aleksic, „Energy, Entropy and Exergy in Communication Networks", Entropy, Vol. 15, No. 10, 2013, pp. 4484–4503.

[33] W. Scharnhorst, „Life Cycle Assessment of Mobile Telephone Networks with Focus on the End-of-Life Phase", Ph.D. Thesis, Lausanne, EPFL, 2006, pages 182.