Introduction to the Special Issue: 5+G Network Energy Consumption, Energy Efficiency and Environmental Impact

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Energy consumption. The Information and Communication Technology (ICT) sector, through its energy consumption, represents between 1.5 % and 4 % of the global Greenhouse Gas (GHG) emissions [1], a footprint that could be twice as large as that of the air transport industry in the most pessimistic estimates. While its growth rate is still subject to discussions, the literature agrees on the fact that this share will not significantly decrease if business goes as usual. The main reason is that traffic demand is still growing, driven not only by end-users' usual expectations of ever-higher quality video for conventional video-on-demand and more recent social-networking-driven applications; but also by the machine-to-machine traffic and by the operation of expanding cloud services. This increasing traffic demand entails an increase in energy consumption, not only in absolute terms but probably also in proportion of the global consumption.

The historical solution has been to produce more energy globally to meet the demand, currently on the order of $6 \cdot 10^{20}$ joules per year, or 19000 gigawatts (GW) on average—for comparison, a typical nuclear reactor produces about 3 GW of thermal energy, harvested into 1 GW of electricity. However, about 80 % of that number comes from fossil fuels, which we should urgently learn to do without; not only to keep climate change to a manageable rate, but also because their extraction is bound to dwindle anyway over the next few decades. Non-fossil electricity production has increased at a maximum historic worldwide rate of: 27 GW/year for nuclear (in 1985); 21 GW/year for hydroelectricity (in 2004); and 60 GW/year (currently) for other renewables (mainly solar and wind power) [2]. Even if these rates could be sustained simultaneously over long periods, just replacing the current consumption of fossil fuels, let alone increasing energy production, would still be a century-long undertaking. Therefore, relying on a sustained growth of the global energy supply seems a somewhat risky bet, which should justify an urgent interest in the alternative: actually curbing ICT energy consumption.

This requires new ways of organizing the networks, seeking optimization across all network layers, including the physical layer. However, although such cross-layer optimization was already an active research subject over a decade ago [3, 4], and modern 5G networks do incorporate some of the techniques developed, the situation has not improved in terms of global consumption. Improvements in energy efficiency were more than offset by traffic growth and rebound effects, and the objective never was to reduce growth in the first place.

Special issue. Our goal was to gather state-of-the-art research in environment-aware networking, focused on the ways to approach the problem most likely to make a difference. This would include still more efficiency improvements, as well as favoring specific uses of low-carbon electricity in data centers and cellular base stations; but also avoiding the rebound effect by taking a holistic view of decreasing the global traffic, via network management techniques whenever possible, as well as enabling and inciting users to moderate their network usage and through other forms of digital sufficiency.

The two invited papers take complementary approaches to the problem. Dominique Chiaroni, Raffaele Luca Amalfi, Jos George, and Maximilian Riegel take the supply side: after presenting a quantitative review of current and forecast global electricity production compared to the energy consumption of several ICT segments, they explore technological solutions, especially how eco-designed combinations of existing technologies (wired optical and electrical; wireless 5G, Wi-Fi and Li-Fi...) could reduce ICT's operational consumption by a factor of almost 3.

On the other hand, Tilman Santarius, Jan C. T. Bieser, Vivian Frick, Mattias Höjer, Maike Gossen, Lorenz M. Hilty, Eva Kern, Johanna Pohl, Friederike Rohde, and Steffen Lange take the demand side, through the concept of sufficiency: decreasing the absolute level of resource and energy use by reducing the levels of production and consumption, explored in the four dimensions of hardware, software, user and economic sufficiency. They discuss the complex interrelations between those, the role of user behavior and public policy, point out difficulties and opportunities, and offer a large number of heterogeneous policy proposals as part of the greater environmental transition.

The contributed papers cover a wide range of topics. Memedhe Ibrahimi, Omran Ayoub, Aryanaz Attarpour, Francesco Musumeci, Andrea Castoldi, Mario Ragni and Massimo Tornatore contribute a genetic algorithm for joint optimization of equipment and energy consumption costs in a type of optical network commonly deployed in the metropolitan/aggregation segment. Their validation in real networks shows the cost-efficiency of sharing transmission lines between legacy and newer optical technologies, allowing for gradually updating networks without having to duplicate the infrastructure.

Louis Golard, Jérôme Louveaux and David Bol propose a very original work, in which they evaluate the energy footprint of 4G and 5G Radio Access Networks (RAN) in Belgium. Their study includes as well a projection of this footprint over the period 2020-2025. In contrast to many papers in the literature that focus on energy efficiency, authors are interested in the *absolute* energy consumption of the network. The 4G Base Station (BS) power consumption model is tuned using experimental on-site measurements, while the 5G model is extrapolated. Several possible 5G deployment scenarios are compared. The conclusions show how the introduction of 5G may have a negative effect on the RAN energy consumption due to the traffic increase and despite a 10 time decrease of the energy intensity. According to the authors, only a rapid decommissioning of 4G could counter-balance the impact of 5G in terms of energy consumption.

Kishalay Bairagi, Sulata Mitra, and Uma Bhattacharya study the energy consumption of a 3D wireless video sensor network under the coverage and connectivity constraints. These networks are deployed to capture videos and images for various applications such as environment monitoring or surveillance. A simple method to save energy consists in reducing the number of active sensors. This reduction has in turn an impact on the coverage leading to constrained optimization problems. Authors propose an extensive and very interesting bibliography on these duty-cycling problems. Then, they formulate an Integer Linear Program that is shown to be NP-hard and propose two solutions: an optimal approach, appropriate for small instances, and a low complexity heuristic based on a genetic algorithm. Numerical results show impressive energy gains (30 to 40% in the studied scenarios) when compared to the state-of-the-art.

Ali Kadhum Idrees and Lina Waleed Jawad propose a variation on the same topic with a new energy-efficient protocol for wireless sensor networks in which a central station gathers information from disseminated sensors. The sensor scheduling algorithm that selectively activates sensors with the goal of saving energy is particularly interesting. It indeed exploits the spatial correlation of the generated data to put sensors with redundant information in sleep mode. Using simulations and real-world sensed data, this approach is shown to be effective compared to the state-of-the-art.

Bartłomiej Blaszczyszyn, Philippe Jacquet, Bernard Mans, and Dalia Popescu study the fundamental trade-offs between delay and energy consumption in vehicular networks with a new theoretical framework. The originality of the approach indeed lies in the hyperfractal model, which is used to characterize mobile and relay nodes locations and which is based on the self-similarity property of urban architectures. Interestingly, this model and the obtained network performance are shown to fit with available real open data and with event-driven simulation results. Authors show that the energy consumption decreases when the routing paths lengths increases and are able to derive a lower bound on the network capacity under the constraint of a path energy. This paper opens new research paths in both fields of stochastic geometry and network protocol design.

Concluding thoughts. While more research is certainly needed in this direction, the papers above show that technologies exist and organization of networks is possible so as to reduce their energy consumption and carbon footprint. By this Special Issue, we hope to spark the curiosity of the reader, in order to invigorate research in this much-needed domain—hopefully reaching a point where all actors of ICT (operators, regulators, users) can be empowered to actually take action and significantly contribute to the transition towards a carbon-neutral future.

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