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For an energy sober network that contributes to a sustainable society

Salah Eddine Elayoubi¹, Eric Hardouin²

¹Université Paris Saclay, CNRS, CentraleSupélec, Laboratoire des Signaux et Systèmes, Gif-Sur-Yvette, France

² Orange, France

Abstract—Sustainability and energy sobriety should guide the “why” and the “how” of 6G. It is mandatory that the 6G infrastructure and services have a very low environmental footprint, but also, and more importantly, the 6G technology should be designed on the 5G basis for enabling added-value services for the society and to mitigate the environment footprint. This paper presents a vision for 6G network as an enabler for a more sustainable society, e.g. by enabling the society of maintenance and care and fostering innovation in the industry. On the other hand, some technology enablers for an energy sober 6G network are presented, along with guidelines for network deployments and for the assessment of the global impact of 6G services.

I. INTRODUCTION

while 5G networks are still in the deployment phase all over the world, the telecommunications research community is imagining the next generation of networks. While many technology bricks such as higher spectrum (such as mmWave, THz and visible light (VL)) and Reflecting Intelligent Surfaces (RIS), are being extensively researched, development of 6G should not be technology-driven, but should respond to the societal needs. While the needs at the horizon of 2030 cannot be completely predicted, two challenges are certainly to be addressed: the omnipresence of Artificial intelligence (AI) in our society and the climatic crisis. The objective of this paper is to situate 6G with respect to these challenges. We show, on one-side, how 6G could federate intelligences for offering sustainability services to the society and the industry, and, on the other side, how the network itself would be energy-sober while offering these services.

The remainder of this paper is organized as follows. In section II, we show how 6G is related to the new concept of the “society of care and maintenance”. Section III provides a technology and architectural view of the 6G network that allows operating under a low energy footprint. Based on these two perspectives (services for sustainability and network energy sobriety), we provide in section IV general rules when deploying and operating new services/infrastructure, for considering the global footprint and novel metrics that include economic and sustainability dimensions. Section V concludes the paper.

II. 6G AS AN ENABLER FOR A SUSTAINABLE SOCIETY

6G needs to enable services that bring value to society and address future societal and environmental stakes [22]. Mobile communications and 6G networks have been

found in the white paper [19] to be highly linked to multiple goals. It is directly linked to SDG 9 and 11 (Industry, innovation and infrastructure and sustainable cities and communities), as we will explained next, and indirectly linked to SDG 3 and 4 (Good health and well-being and quality education) [21].

A. Fostering innovation

6G should foster innovation by enabling use cases such as immersive experience, e.g., for the Metaverse [22]. 6G should also enable the development of industry 4.0, for instance through the generalization of digital twins. Robots and autonomous systems are also to be enabled by 6G, as well as the coexistence of robots and human workers sharing the same space (so-called cobots) [22].

It is worth noting that these use cases may necessitate higher data rates and/or lower latencies than possible with 5G. One of the big issues in the future will therefore be to ensure a sufficient coverage in uplink and downlink from macro radio sites to enable these types of services. Network densification could also be considered but would have a high carbon footprint and a high cost.

B. Enabling the society of care and maintenance

Innovation is essential for our modern societies but must not constitute a unique progress objective. Circular economy (CE) has been considered in the past decade as a way forward, that starts with innovation, leading to manufacturing at a large scale, product use/consumption, and then recycling [5]. IoT and 5G are seen as enablers of such a CE and [20] proposed a 5G-enabled architecture that creates a class of “Looping Smart Assets”, leveraging on IoT, SDN and cloud technologies.

6G, as a natural continuity of 5G, should be designed as an essential enabler of circular economy. We however advocate a step forward, with the objective of being part of the “maintenance and care” society. Indeed, recent studies such as [3] point out the limitations of circular economy, as a “pure product of the consumer society, that only cares about producing, consuming and recycling”. Maintenance is then regarded as a way for expanding the life of things, retarding as much as possible the moments of disposal and recycling, and a whole research branch, the so-called “maintenance and repair studies”, is being developed [3]. Our vision is that 6G should leverage on the ubiquitous connectivity and the massive

sensor capability for enabling predictive maintenance before breakdown, and assist workers who participate in the daily life of technologies, long after their initial deployment, in maintaining infrastructures alive and operational. To be more precise, among the 7 steps of the circular economy model, as defined in [26] (Raw materials, sustainable design, production, distribution, consumption/reuse/repair, collection and waste management), the fifth step is expanded with the approach of care and maintenance. For this purpose, 6G should support massive IoT deployments for allowing our current transportation, energy, telecommunication, water, etc., infrastructures to long live, avoiding usage of natural resources for constructing new ones.

While maintenance refers in general to “things”, recent research [3] about a “care and maintenance society” proposes a unified approach for taking care of the people, the things and the environment. 6G should enable the care for people through the generalization of eHealth services, as well as environment monitoring.

C. Enabling technologies for a sustainable society

In the following, we present key 6G technologies that enable the above-mentioned services.

1) Enablers for an innovative and efficient industry:

a) *Fog computing*: For coping with the distributed nature of communications in industrial environments with a multiplicity of vehicles/robots/machines, a new computing paradigm, edge/fog computing, has emerged for 4G and 5G networks. [29] proposed the architecture of fog RANs (F-RANs), which motivates a paradigm shift from centralised cloud computing to distributed fog/edge computing. Fog computing enables the orchestration of federated learning applications on the continuum from the devices to the Cloud, including intermediate processing nodes in the RAN, paving the road for distributed inference [17]. In addition to inference from local data collected by devices, fog computing could also enable AI as a Service (AIaaS) [35], where the local processing resources could be exploited for third party AI applications.

b) *Goal-oriented communications*: Instead of behaving as a pipe of data, 6G is expected to enable connected intelligence beyond connected things [17], and this evolution is a main enabler for industrial applications. For achieving this vision, a new communication paradigm has emerged in recent years, that is goal-oriented communications. With opposition to the quality of service objectives set for specific communications services, goal is here defined for a specific application, not in terms of formulated QoS targets, but in terms of the performance of the achieved application task. The idea is that what really matters is the impact that the received bits have on the interpretation of the meaning by an intelligent receiver, or on the accomplishment of a common goal between the transmitter and the receiver [33] (note that this approach is sometimes called task-oriented, as in [7]). First applications of this paradigm focus on the sampling

of data from the source, so that only the information that is strictly relevant to the effective fulfillment of the goal is transmitted (see for instance [23] for real-time tracking applications and [31] [34] for edge learning). Another stream of goal-oriented works is related to the joint optimization of the network and application (see for instance [13] for image retrieval at the edge with communication constraints, [6] for vehicle platooning controller design under channel imperfections, and the 6G paradigm of joint communications and sensing [36]).

2) Enablers for the society of maintenance and care:

a) *Massive IoT*: Massive MTC was one of the three pillars of 5G, and is expected to be the principal enabler for the society of care and maintenance, allowing to deploy battery-powered/batteryless devices on the critical infrastructure. Infrastructure-monitoring sensors typically send few bytes per day, and, are expected, even with the current 5G technology, to operate on their battery for several years. Furthermore, wireless information and energy provision (WIEP) is being researched for 6G mMTC [11], and energy harvesting (solar, mechanical, etc.) will further extend the lifetime of 6G sensors.

b) *Tactile Internet*: Both the innovative and services (Metaverse, industry 4.0, automation systems) and the society of care (remote healthcare, online education) call for the deployment of the so-called Tactile Internet (TI), defined in [8] as supporting haptic media including tactile (sense of touch) and kinesthetic (muscle movement) interactions. Human-type TI services (VR/AR, teleoperation, etc) have very stringent delay requirements, while mission-critical machine-type communications (industrial automation, autonomous vehicles/drones) are very sensitive to packet losses [9]. 5G URLLC already achieved some of the TI services requirements, with its 1 ms delay for small packets and $10^{-5} - 10^{-7}$ packet loss probability in the RAN. It is still unclear whether 6G should fulfill more stringent requirements on the RAN, but mastering the end-to-end latency and associating URLLC with high data rate, massive access, and high mobility should be the pillars for 6G extreme URLLC [25].

Many research directions are open in this field. In particular, the concept of 5G slicing, where each RAN slice corresponds to a service (eMBB, URLLC, or mMTC), potentially associated with a (vertical) user [4], should evolve for TI. In particular, for almost every TI use case, the interaction between physical and virtual worlds involves various types of traffic, with different profiles and QoS, that need to be synchronized and harmonized as they tend to achieve the same goal. Composite metrics, associating performance of the URLLC flow (haptic feedback) and of the eMBB stream (video), as proposed in [24], are to be computed, monitored and controlled, calling for a new definition of 6G slicing for TI applications, with an internal orchestration of resources.

Figure 1 shows a fog computing architecture for 6G, where goal-oriented communications enable distributed sensing and efficient control (robotics, platooning, etc.),

and TI enables industrial robotics and eHealth. Intelligent functions are deployed on the extreme edge (devices, access points), on the near edge, and in the cloud.

III. OPERATING WITH MINIMAL IMPACT

The above description provides a vision for 6G networks as an enabler for an innovative and sustainable society. However, as part of this vision, we stress out that the network itself should have minimal environmental impact. Even if 6G infrastructure, following the trend of 5G, is expected to be more energy efficient, a 6G network should have the following two properties:

- (P1) First, the energy consumption should scale gracefully with the traffic load, with a near-zero energy consumption at zero load.
- (P2) And, second, the energy per occupied radio resource should be minimized, so that the global 6G energy consumption is mastered, even if much more spectrum is used compared to 4G/5G systems.

We expose in the following the main 6G technologies and how they contribute to these two properties.

A. RIS

The Reconfigurable, Intelligent, and Sustainable Environments (RISE) communications paradigm, enabled by the deployment of a novel layer-0 composed of RISs [32], is considered as a key 6G architectural innovation, and is expected to achieve reduced energy consumption when network densification is needed compared to classical base stations. RIS are nearly passive, and may be used for controlling the radio channel in a way that ensures targeted performance boosting while avoiding high power transmission [30], thus reducing the energy per occupied resource (P2). In addition, RISs do not consume any energy while inactive, while classical relays do (P1).

However, several issues are still to be addressed for enabling sustainable RISE. RISs are not completely passive especially as they need to implement Channel acquisition and tracking (CAT), either by dedicated hardware (case of passive RIS) or by integrated sensing and tracking (active RIS) [32]. Second, the energy consumed by the hardware implementing the necessary AI for learning the optimal RIS configuration should be taken into consideration. Although there have been several works that assessed by simulation the energy efficiency of RIS-aided cell free systems [30, 12], a holistic approach comparing the energy consumption of a 5G dense network with a RIS-aided 6G network achieving the same performance is still lacking. Finally, the environmental impact of building RIS and their life-cycle analysis should be considered in the whole 6G network sustainability assessment.

B. Native integration of AI in the lower layers

It is well-known since 4G network deployments that AI-based load management between different network layers is a main enabler for an efficient sleep mode of the base stations, and thus a near-zero energy for zero

load (P1) [27]. [17] expects that machine learning (ML) and artificial intelligence (AI) will play a defining role in the development of 6G networks end-to-end across the design, deployment, and operational phases, while [10] proposes the concept of AI-native air interface (AI-AI), where AI replaces processing blocks or designs parts of the air interface at link level, and optimizes the MAC protocol design. From energy consumption point of view, AI-AI should enable a pilot-less air interface (as in the use case of [10]), thus contributing to (P2). We also propose Multi-Agent Reinforcement Learning (MARL) that adapts resource allocation, power management and load management for enabling an efficient sleep mode, thus contributing to (P1).

C. 6G network of subnetworks

Due to its ultra-high heterogeneity, 6G architecture is envisioned as a “network of subnetworks” [17], with a local management associated with a hierarchical coordination, instead of a forced harmonization and a centralized management. Each of this subnetworks will have its different characteristics such as coverage, capacity, PHY layer technology and resource allocation. With the native AI integration, a local management should allow devices to connect to the best subnetwork at any time from coverage and energy efficiency perspective, contributing to (P2). An example and referring to figure 1, several subnetworks, with possibly overlapping coverage and different technologies/spectrum bands, coexist in the 6G network. These subnetworks are managed locally and coordinated by orchestration functions in the edge or higher in the hierarchy, in order to achieve the minimal energy consumption while achieving the application goals.

D. O-RAN

The Open RAN (O-RAN) Alliance has been founded by mobile operators to drive the evolution of the RAN towards more openness and intelligence. SDN and NFV are key enablers of O-RAN architecture, allowing 5G networks to fully profit from non-Real Time (non-RT) and near-Real Time (near-RT) RAN Intelligent Controllers (RIC) for all network management tasks. O-RAN RICs have been originally designed to incorporate AI in all management tasks, making O-RAN a natural enabler for a smart, agile and self-adaptable 6G network [18].

From sustainability point of view, O-RAN near-RT RIC will contribute to an agile management of the radio resources, contributing to (P2) on the radio interface. Moreover, the fog computing paradigm introduced above for industrial IoT poses the challenge of placing the processing functions on the continuum from devices to the cloud. Such placement can be optimized for minimizing energy consumption while ensuring performance [14], and the fog function placement may be integrated within the global 6G O-RAN architecture.

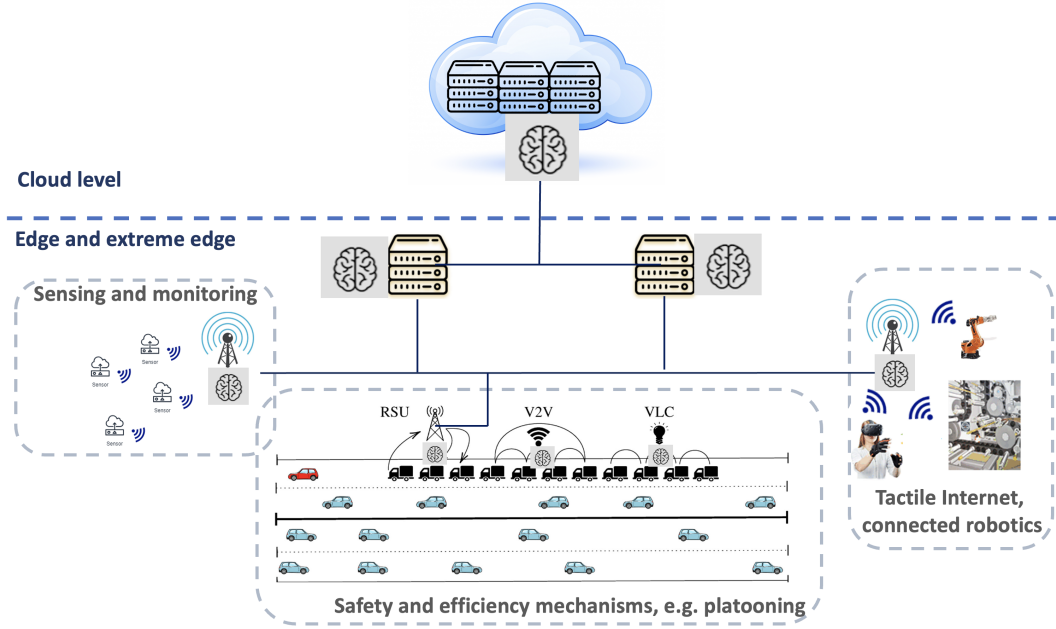


Fig. 1. Fog computing for industrial and maintenance applications.

E. Digital twin-based network management

Digital twins-enabled 6G network management has SDN/NFV as a basic requirement and is fully compatible with the O-RAN architecture[18]. The DT of the network will perform offline analysis and real-time control, for an operational twin of the network [15]. Such management solution will enable descriptive analytics, diagnostic analytics, predictive analytics, and prescriptive analytics [17], thus enabling a large scale vision of the network and its subnetworks. In particular, predictive analytics of the traffic, loads and interferences will enable prescriptive actions such as putting some base stations into sleep mode and awakening others, and balancing traffic between subnetworks, contributing to both (P1) and (P2).

The largest challenge encountered with a digital twin-based management is data transfer, that might saturate communication networks and entail large energy consumption. An important research direction is to use distributed deep learning or federated learning associated with fog computing for building a network of local digital twins, thus minimizing the data transfer.

IV. DESIGN AND DEPLOYMENT RULES

Having exposed the main 6G sustainability enablers, we now draw general deployment and operation rules.

A. Deployment phase

1) *Technology and subnetwork choice*: The deployment of the 6G network should be service driven, in opposition to the technology-driven vision. As 6G architecture should be based on the integration of subnetworks, the use of existing infrastructure should be privileged as long as it is possible. This calls for a larger role for software upgrades, and for maintenance and repair.

2) *Low footprint 6G equipment*: It is highly expected that, despite the massive reuse of legacy infrastructure, new 6G equipment will be needed in several scenarios, in particular for supporting new frequency bands. A special attention should then be given to the environmental footprint of new equipment, including its whole lifecycle from ore mining to the end of life. Using recycled material and imposing hardware design rules that ease maintenance are important. Also, the long-term availability of critical materials foreseen to be required by some 6G features should be assessed prior to technology design choices.

B. Operation phase

1) *Operating under a strict energy constraint*: In operation mode, the objective is to avoid increasing the energy consumption, even if much more traffic is to be served. The classical approach's objective is to increase energy efficiency (in bit/Joule), defined as the ratio between the served traffic (in bit/s) to the consumed power (in Watt) [16]. This approach leads to two complementary levers:

- 1) Increase spectral efficiency by implementing technologies such as massive MIMO, leading to larger spatial multiplexing of users, with a higher energy cost, highly compensated by the traffic increase. The spectral efficiency also profits from adding new spectrum carriers in the higher bands (more available spectrum with a larger number of antennas).
- 2) Implement sleep mode [27], leading to almost zero-Watt consumption in zero-traffic scenarios.

However, the largest gains in energy efficiency, when moving from 4G to 5G, were obtained by the increased spectral efficiency that allows increasing the numerator (traffic) by several folds, while increasing the denominator (power consumption) by a small factor. 6G network

operation should give more importance to the absolute energy consumption, for instance by operating under a strict energy consumption constraint. This approach is expected to lead to a paradigm shift in the network operation, as a slight degradation of the KPIs (throughput and/or latency) could be needed in some scenarios.

2) *Tight integration of renewable energy sources:* As 6G will feature numerous fog/edge micro datacenters, as discussed above, an integrated management of fog datacenters, renewable energy sources and AI learning applications will be beneficial. Instead of moving energy surplus across transmission lines or storing it in batteries, idle servers close to renewable sources are exploited whenever there is an energy surplus to run energy consuming ML algorithms. Federated learning framework will allow training the model on each local fog, and then aggregating the updates to create a global model, reducing in the same time the amount of data to be transferred.

C. Global impact assessment

We have discussed above how the environmental footprint should be considered on the whole lifecycle of the network elements, and there are already results in the literature for this footprint assessment [28]. However, these negative impacts have to be put in one side on the balance, and compared to the positive societal impact, as explained in section II and illustrated in figure 2. When deploying a 6G infrastructure, a global metric combining both sides of the balance should ideally be computed for operational deployment decisions.

Having defined this high level principle, its practical implementation is not straightforward. A common approach in 6G research is to define Key Value Indicators (KVI), e.g. in relation to trustworthiness, sustainability, business value, fairness, security, etc. [1]. However, capturing these KVIs in a classical cost-benefit analysis (CBA) may not be possible. Indeed, these KVIs, in addition to metrics such as reduced CO2 emissions from other sectors, are hard to be transformed into monetary outcomes in a CBA. Alternative approaches such as Social Return On Investment (SROI) may be more valuable for capturing the global impact of 6G networks. These approaches express the impact as a ratio, for instance $n : 1$, meaning that a dollar invested in the project/organization generates a social value of n dollars [2], which shows the main difficulty of SROI, as a common monetization approach for non-monetary impacts is still to be standardized. In addition, these approaches have been very popular in the third sector (non-profit organizations) in the recent years, but their adaptation to profit-based businesses like 6G network and service deployments is still an open research problem. Figure 2 shows examples of negative externalities and positive impact of the 6G network and services.

V. CONCLUSIONS

In this paper, we have presented a vision on 6G network engineering that is sustainability-oriented. We

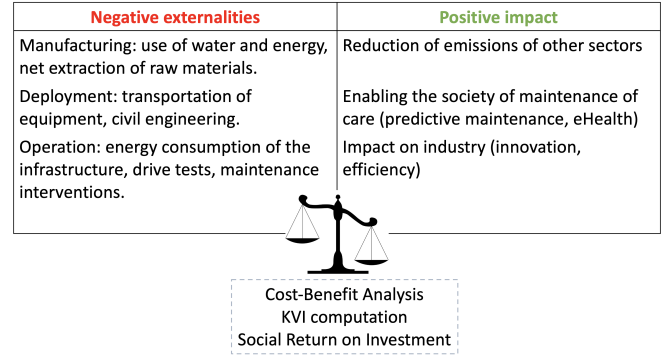


Fig. 2. Impact assessment

have shown how 6G services should foster sustainability of the society, and how 6G networks could be energy-sober. We have identified several open research problems related to the network engineering and management, but also on new networking paradigms such as goal-oriented communications. This vision could not be achieved without the commitment of the end users, including verticals, as well as application providers. Transparency about the the energy consumption and CO2 emissions and the KVI/SROI should increase acceptability, especially when operating under a strict energy constraint.

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