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Standardization Roadmap Toward Sustainable 6G

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Abstract

Recent years have brought a consensus in the telecommunications industry that a strong reduction of overall energy consumption and CO_2e emission of running networks is a critical goal that must be achieved. For this to be possible, a mindset change is necessary in the industry, in particular in the relevant standards setting organizations, such as 3GPP. A whole new infrastructure for measuring energy consumption at various levels of granularity (e.g., per service, per user), measurement data collection and dissemination to relevant parties (e.g., service users, other domains), as well as optimized usage of available energy must be in place in the networks to enable this transition towards sustainable networks. This paper presents an approach on how this infrastructure can be standardized in 3GPP and references efforts in related standardization bodies. We analyze the current status of sustainability related efforts in 3GPP, identify the main gaps that need to be bridged, and provide concrete steps in terms of enhancing existing technical specifications or creation of new ones, to make the said infrastructure operational. We also report on the concrete efforts made within the EU funded project EXIGENCE to realize this vision.

Introduction

Communication systems are becoming increasingly more energy-efficient. However, their total Energy Consumption (EC) is expected to grow, due to the well-known rebound effect [1], [2]: paradoxically, increased efficiency leads to increased usage, which, in turn, increases EC and Carbon diOxide equivalent (CO_2e) production. Moreover, advanced applications and services like Artificial Intelligence (AI) and autonomous vehicles that 5G Advanced (5GA) and 6G are expected to support, could further increase network EC and, ergo, its carbon-footprint. According to sources [3], [4], Information and Communication Technologies (ICT) global Green House Gas emissions ranges between 1.8-2.8% of the global emissions, and the telecommunication sector was responsible for 1.6% of global emissions in 2022. Interestingly, environmental studies [5] indicate that ICT services have the potential to decrease global CO_2e of the society by about 15% by 2030 – which will come with an even higher penetration of ICT and higher EC. With this, ICT services will certainly further increase their relative share in the overall CO_2e emissions.

In this regard, potential solutions to measure, optimize and reduce EC and CO_2e posture of communication networks are being investigated [1]. With today's typical Mobile Network Operator (MNO) services, a rough per-service EC estimation can be realized based on transferred data volumes. While possibly sufficient for best effort Mobile Broadband services (MBB), this cannot be presumed accurate for a more complex service-mix expected in 5GA, e.g., Ultra-Reliable Low-Latency Communications (URLLC) or Non Public Networks (NPNs). Moreover, they would fail if they are applied to next generation mobile system (6G) services like sensing, in-network computing and AI model training because, the EC and CO_2e thereof are not directly – or sometimes not at all related to transported data volumes. If regulatory [6] or financial aspects like carbon markets also get involved, then accurate measurements of EC and carbon footprint of organizations and entities with explainable methodology will be enforced. For instance, if entities are charged for their EC or CO_2e, then they must receive accurate measurements and comprehensible attribution of their EC/CO_2e share. Moreover, actual power grid deployments show that ratio of renewable energy varies with respect to time and location, as do energy usage patterns. Hence, carbon footprint measurements are not trivial, and precise figures cannot be easily estimated from the measured EC, let alone from the transferred data volume. Instead, measuring CO_2e requires at least measurement of the consumed energy and mapping of this consumed energy to the corresponding carbon emission with respect to the source of energy supplied to the entities in the executing environment during the time of measurement.

Relevant ICT standardization bodies and industry have recognized the trend towards quantifying EC and CO_2e at the service level, as well as the need to support advanced features that assist in their reduction. In this regard, this paper aims at addressing the current standardization trends that facilitate sustainable design and use

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of future ICT systems, where sustainability refers to reducing the EC and carbon-footprint of operational ICT systems, identifies important gaps and proposes a way forward to maintaining sustainability. The paper is organized as follows: first, we present current sustainability-oriented activities in the standardization of 5G and 5GA systems in the "Standardization on Sustainable Mobile Networks" section. The "Towards 6G: Gaps in Standardization" section presents relevant gaps that need to be addressed on the way towards 6G. The initial guidelines for addressing the identified gaps are subsequently presented in the "Way Forward" section, followed with the efforts and results from Horizon Europe research project EXIGENCE [7] in the "Exigence Position and Contribution" section. The "Conclusion" section concludes the paper.

Standardization on Sustainable Mobile Networks

The 3rd Generation Partnership Project (3GPP) [8] standardized metrics to estimate EC of mobile network as a single domain in Release 18 (TS 28.550[1], TS 28.554). In Release 19, energy efficiency became a service criterion with a study item in 3GPP Service & System Aspects Working Group 1 (SA1) that produced corresponding use cases and requirements (TR 22.882). Subsequently, the consolidated requirements from this study were included in TS 22.261 (Section 6.15a). Similarly, Release 19 TR 28.880 presents use cases and requirements for performance measures and exposure methods for renewables, CO_2e exposure and some related features based on EC input. Energy related requirements from TS 22.261 (Rel.19 & 20) led to the 3GPP Service and System Aspects Working Group 2 (SA2) study item TR 23.700-66 (Rel.19) which identified the following three key issues: 1) Network energy-related information exposure, 2) Subscription and policy control to support energy efficiency and energy saving as service criteria and, 3) 5th Generation mobile communication System (5GS) enhancements for network energy saving and efficiency. It further studies energy-related aspects to provide various solutions that address the identified key issues, where various proposals for new network functions are proposed to collect energy-related information or information that has impact on EC and/or Energy Efficiency (EE) in order to derive an estimation of the consumed energy. Finally, the Energy Information Function (EIF) was standardized in TS 23.501 (Rel.19).

Internet Engineering Task Force (IETF) [9] has recently chartered Getting Ready for Energy-Efficient Networking (GREEN) working group for the development of data models that could allow measurement of energy and reporting through network-level metrics. The initial work is centered on the identification of use cases to derive these data models, including ways to aggregate EC/CO_2e information over a given flow/path (cf. Green Networking Metrics, Path Energy Traffic Ratio API – PETRA). Additional efforts are spanning across other working groups that are pivoting around the notion of energy-awareness services.

European Telecommunications Standards Institute (ETSI) [10] also provides comprehensive work on sustainability covering wide range of areas. ETSI's Technical Committee on Environmental Engineering develops standards related to energy efficiency in ICT equipment and networks (e.g., ETSI ES 203 228 V1.3.1 defines metrics and methods for mobile network energy performance measurement). Additionally, ETSI's Industry Specification Group on Experiential Networked Intelligence (ETSI ISG ENI) addresses AI techniques and their role for network operations optimization, adjusting them based on user needs, as well as environmental conditions and business goals. Finally, industry fora such as NextG Alliance with its Green G working group has published a noticeable report [11] highlighting that manufacturing stage may be the main cause of CO_2e in mobile communications devices. In its Green Future Networks project, Next Generation Mobile Networks Alliance suggests service-level measurements [12]. For further details on IETF and ETSI standards, we refer the readers to Green ICT Digest section on the Exigence website [7].

This section discussed the most prominent sustainability-oriented activities in the major standardization organizations of 5G and 5GA systems.

Towards 6G: Gaps in Standardization

In view of the expected services in 6G and upcoming legislation(s) [6], steps described above point in the right direction, but they are insufficient. We identify the following gaps in the ongoing standardization efforts.

Missing Mechanisms for Obtaining Accurate Ecodata Information in Mobile Networks

Current telecommunication networks lack mechanisms to accurately measure EC at service level on participating system entities (i.e., Radio Access Network (RAN), Core Network, transport, etc.). Estimating EC through transported data volume (3GPP's approach) is a good start. However, it is inaccurate, as it disregards both the service realization (e.g., energy profiles of the involved system entities) and the service complexity with respect to EC (e.g., a compute-intensive service versus MBB). For accurate EC-based accounting, service type, data volume, data rate, compute effort, energy-mix, location, time, reliability, security and quality at serving system entities should also be considered.

Further, today, EC is translated to corresponding CO_2e using rough-grained models, which do not account for time and location-dependent fluctuations of the green energy supply as described in the "Introduction" section. Measuring CO_2e is not trivial, not only due to the dynamic nature of the energy-mix, but also due to the various system entities with different energy versus load profiles. However, this is difficult to achieve in current mobile system architecture design with their separation of concerns; information regarding the network entities executing a service session and their load profile is only available in the control plane while information regarding the energy-mix and location-dependent fluctuations of the network entities is only available in the management plane.

Lack of Ecodata Awareness of Users/Subscribers

Regulating the service usage using availability of green energy emerges as an interesting new

[1] 3GPP documents (TS and TR) are available from 3GPP Portal: https://portal.3gpp.org/Specifications.aspx

method, in particular when network and Application Service Providers (ASP) are approaching their CO_2e limits. In contrast, prevailing flat-rate charging models accelerate environmentally-irresponsible consumptions. ICT domains lack the mechanisms to motivate end-users to consume services responsibly. Specifically, there are no mechanisms to raise user awareness on the energy and carbon-footprint arising from their service consumptions; no alternatives to modify their consumption; no incentives for environmentally-responsible users to take corrective actions; and, no mechanisms for users to signal their willingness to be served in energy-efficient manner.

Lack of Inter-Domain Cooperation

End-to-end (E2E) ICT service delivery involves many domains, mobile networks are just one of them, albeit a prominent one. In terms of service-level ecodata, their role could span from connecting subscribers to relevant providers in the service chain to retrieve EC/CO_2e data (ecodata authority resolution) to transparently aggregating EC/CO_2e data along the service chain (ecodata provider) with required accuracy and precision. However, with the 3GPP features planned so far for 5G, the mobile networks can only (roughly) estimate subscribers' EC information from their network. Estimating the EC from known usage, in particular without relationship to infrastructure (e.g., volume-based estimations), within a single domain can be based on a pre-established knowledge model and is therefore, relatively straightforward. However, to measure EC/CO_2e for service consumption of end-users spanning several domains, a deeper understanding of the impact of different network entities and functions on EC and CO_2e throughout the E2E chain is necessary.

Frequently, ICT service function chains involve several players, and users do not necessarily have explicit contractual relationship with all participating providers. Inter-domain cooperation can help in understanding effects that particular settings have on EC (e.g., routing effort versus optimal path). This introduces a need for providers to either forward the ecodata information downlink in service chain or aggregate such information. However, 3GPP lacks mechanisms to receive (expose) ecodata information from (to) external participating domains and to aggregate this information for an E2E service.

Lack of Verifiable Ecodata Attribution

Every Service Provider and Consumer (user, MNO, ASP) is interested in reducing their EC and CO_2e and, in particular, would like to know the precise CO_2e amount that they, are made/held accountable for, which can be leveraged on, e.g., carbon markets like the European Union Emission Trading System (EU ETS). The more CO_2e a service provider can credibly attribute to the service subscribers, the more carbon credit the provider can claim on carbon market. This creates a strong incentive and commercial interest, which usually falls under typical audit obligations. As all participants in a service chain might have their own interests, mechanisms are needed to avoid/prevent/limit inaccurate reports and verify their validity. Today's networks lack such mechanisms.

This section discussed the gaps in current standardizations that must be addressed in order to support the envisioned 6G applications and services.

Way Forward

Based on the observations above, we propose the following measures for the telecommunications domain.

Proposal 1: Accurate Ecodata Measurements

As a precondition for obtaining accurate ecodata measurements in mobile networks, we propose that vendors equip their devices with Application Programming Interfaces (APIs) to configure actual EC measurements of various individual applications/services/tasks running on that device, enabling accurate and verifiable attribution of overall device EC to the logical entities executed on that device (sessions or flows; tasks, threads or processes, etc.). This is similar to the existing efforts in the compute domain, e.g., Power API using Linux kernel's perf API to access available hardware performance sensors such as those using Running Average Power Limit (RAPL) technology, available, e.g., on Intel and AMD CPUs. Such hardware capabilities and APIs would enable MNOs to accurately measure EC of their users when needed and obtain corresponding CO_2e (using energy-mix and carbon intensity information from energy suppliers).

Proposal 2: Timely Exposure of Ecodata

Users should be informed about their eco-impact not only at the end of a billing cycle, but also regularly, through ecodata reports during service consumption, proactively or on demand. This would enable service users to make informed decisions. Thus, 6G networks should be equipped with mechanisms and procedures to be able to accurately measure and report ecodata of the services consumed by subscribers at various intervals during service execution.

Proposal 3: Inter-Domain Ecodata Reporting

All domains participating in a service implementation must expose total ecodata attributable to a user / service instance, at granularity and time resolution suitable for that service. Note that the 3GPP system itself can be a user in this scope, e.g., in case of a remotely hosted Network Function. A 3GPP subscriber is another obvious example of a user of the provided eMBB service, e.g., of the Protocol Data Unit (PDU) Session, or of a 5G QoS Flow. The necessary architectural enhancements for the service-level EC measurements, energy usage and carbon footprint exposure and carbon emission accounting must be introduced in the mobile networks to allow a 3GPP network to expose ecodata to externals, and to receive it for services used from other domains or networks. This allows cooperative EC optimization.

Proposal 4: Incentivize CO_2e Reduction

Mobile networks should enable incentivization of carbon emission reduction. Mechanisms to accurately measure and optimize service execution should be complemented with the identification of dynamic opportunities for users to reduce their service consumption via alternative service consumption options, e.g., consume with lower QoS, or later, when renewable energy is available, and receive carbon-credit in exchange to monetize carbon emission reduction. To enforce that, users should have ways to express their choices for service consumption. Although incentivization is out of 3GPP scope, it is a strong enabler for reducing CO_2e emissions.

This section presented the necessary guidelines for relevant standardization organizations to address the gaps identified in the "Towards 6G: Gaps in Standardization" section.

EXIGENCE Position and Contribution

The analysis presented so far, the identified gaps and the proposals to bridge them are the result of our efforts within the EXIGENCE (SNS JU) project [7]. The project aims to devise a novel approach to reduce EC and CO_2e of ICT services in the next-generation mobile systems (6G) through advocating for *measure-optimize-incentivize* methodology. Specifically:

- **Measure (cf. Proposals 1, 2 and 3):** By measuring ecodata at the level of individual services, a network operator gains precise knowledge of the energy profile of their service execution in runtime, e.g., which system nodes consume the most energy for which service, and how services can be (re) allocated to reduce EC. Service-level energy information should be exposed by all providers, such that, acting as users, any party can get EC/CO_2e reports for the parts outsourced to third parties (e.g., Core Network running on an external Cloud).
- **Optimize (cf. Proposals 1 and 3):** Once a detailed picture of the EC in the network is available, the network operator can apply various optimization techniques to reduce the EC and CO_2e, e.g., by shifting load away from heavily loaded nodes (such as base stations), and selecting energy and CO_2e aware service delivery paths (e.g., during handovers).
- **Incentivize (cf. Proposal 4):** With accurate information on EC and CO_2e status of each individual service, and their exposure to the service consumer, the operator gains a lever to use in order to involve the service end-user in service delivery related decisions, e.g., select an eco-mode alternative for a service to consume less energy. Please note the inter-domain aspect here: end-user should be presented with service-related ecodata spanning all domains involved in the service delivery.

One can see that the first, crucial step in realizing this vision is instrumentation of an EC/CO2e measurement architecture. This has been the main (standardization-related) focus of EXIGENCE so far. To this end, EXIGENCE has made several standardization contributions:

- In 3GPP, setting up relevant use cases, formulating requirements in 3GPP SA1, and defining solutions in 3GPP SA2.
- In ETSI PDL ISG, creating energy-related work items.
- In IETF GREEN WG, creating energy-related drafts.

3GPP Contributions

Three use cases were approved in SA1 for Release 20 and raised requirements for subsequent work in SA2. Additionally, during Release 19, new solutions and enhancements were also approved in SA2.

3GPP SA1 Contributions

- *Use case on Energy Consumption and CO_2e transparency in the end-to-end service chain:* Service providers like MNOs want to reduce the EC and CO_2e of their service offerings, e.g., to reduce OPEX. Hence, they should offer green services E2E with the lowest possible EC and CO_2e. To achieve this, service providers should possess the knowledge of EC and CO_2e of all the participating entities in E2E service delivery chain at various granularities. In this regard, this use case (S1-242422) relies on a series of EC and CO_2e measurements, interoperability between different participating domains, and necessary capabilities. With an accompanying service flow describing the expected operation (for details please see S1-242422) and investigation on the lack of existing features to fulfil such requirements, this use case concludes that flexible novel architectural patterns, new modules and interfaces with additional procedures for overall ICT service EC and CO_2e measurement, and per-domain energy usage and/or carbon footprint reduction mechanisms are needed. The respective requirement introduced in 3GPP is as follows: *The 3GPP network shall be able to provide exposure of Energy Consumption data and CO_2e data for a specific service data flow, to an Application Function* (cf. Proposal 2 & 3).
- *Use case on Green social media and email content download:* The size of attachments sent over mobile services like instant messaging and email has increased drastically in recent years. Moreover, data consumption is on an upward trajectory and it is expected to grow strongly. Therefore, it is essential to address the challenges brought forth by this consumption behaviour with regards to achieving carbon neutrality. In this regard, this use case (S1-242543) proposes to reduce the carbon impact of instant messaging and email services and similar, other non-time critical data transfers, like firmware downloads, uploads of social media or email attachments and downloads from OTT video providers by deferring the downloads to when the energy-mix and/or radio conditions are more favourable. With an accompanying service flow describing the expected operation (for details please see S1-242543) and investigation on the lack of existing features to achieve such functionality, this use case concludes that users should be informed about their carbon impact and have an opportunity to reduce their expected carbon footprint. The respective requirement introduced in 3GPP is as follows: *The 3GPP system shall be able to expose information to an Application Function in the*

[2] The S1-* and S2-* documents can be found here: https://www.3gpp.org/ftp/tsg_sa/

Project Contribution	Proposal	Planned Next Steps
S1-242422	1, 2, 3, 4	These use cases were accepted in 3GPP SA1 "energy efficiency as a service criterion" study resulting in normative service requirements documented in TS 22.261. These normative requirements will be the basis for SA2 work where the key issues for meeting these requirements will be identified, and corresponding solutions will be generatd, subsequently deriving stage 2 normative specifications. Following that, detailed stage 3 specifications will be derived by respective 3GPP working groups.
S1-242543	1, 2	
S1-241410	1, 2, 4	
S2-2403455	2	This solution was approved for inclusion in the Technical Specification document to be generated by the 3GPP SA2 FS_EnergySys Study Item (SI).
S2-2401927	4	This contribution aims to realize the proposal 4 through contributing to the 3GPP FS_EnergySys Study Item with energy saving requirement in mobile networks at network slice granularity. The aim is to incorporate the solution into the TS document to be generated by the corresponding 3GPP SA2 WI.
ETSI ISG PDL-0031_Energy_CDS	1, 3, 4	This contribution was approved as a WI leading to studies on how EC data can be shared in a trustworthy manner with PDL service.
IETF draft-contreras-nmrg-green-intent-01	4	These drafts were approved resulting in generation of use cases, and solutions for consumers to apply eco-mode and facilitate the expresession of their expectations w.r.t. energy. They are expected to continue their progress in their respective IETF groups.
IETF draft-stephan-green-use-cases-00	1, 2, 3	
IETF draft-contreras-pim-eco-mode-00	4	

TABLE 1. Exigence standardization contribution.

network on the (expected) energy related characteristics applicable to the serving site/network (cf. Proposal 2 & 3).

- *Use case on Carbon emission charging:* In order to design solutions for achieving carbon neutrality in the ICT sector, carbon footprint's impact across the E2E service delivery chain should be investigated. This requires measuring and attributing energy usage and carbon footprint to the rightful parties. In this regard, this use case (S1-241410), relying on a series of energy measurements, impact of different network nodes with different energy-mix and cross-domain interoperability proposes to measure EC and CO_2e across E2E service delivery chain and attribute them to the service-consumers for their service usage. With a supporting service flow describing the expected operation (for details please see S1-241410) and investigation on the lack of existing functionality to achieve this, the use case concludes that new modules and interfaces with additional procedures for the overall ICT service measurement, and per-domain energy usage and carbon footprint exposure mechanisms are needed. The respective requirement introduced in 3GPP is as follows: *The 3GPP network shall be able to collect information on energy consumption and carbon emission that are attributed to the subscriber* (cf. Proposal 1, 2 & 3).

3GPP SA2 Contributions

- A solution is proposed in S2-2403455 to enhance Network Function (NF) selection in the core network based on energy (cf. Proposal 2 & 3). The solution contains new control plane signalling messages, procedures describing energy related information exchange between different NFs and associated enhancements in Network Repository Function (NRF) based on energy states, analytics, and other energy related information. The following enhancements are proposed: 1) Service provider NFs register their energy related information at NRF. Alternatively, Operations, Administration, and Maintenance (OAM) can (re-)configure this; 2) NF discovery procedure at NRF is enhanced with energy-related NF discovery query parameters (e.g., energy aware NF discovery policy/criteria) based on new energy-related policies; 3) NF service consumer considers energy related information from NF profiles discovered from NRF for selecting a target NF; and finally, 4) NF Status Subscribe/Notify procedure is enhanced with energy related information between consumer NF and NRF.
- A solution is proposed in S2-2401927 to enable EC exposure and control in Mobile Core Network for energy saving at slice (cf. Proposal 2 & 3). Essentially, based on EC thresholds, energy saving authorization information from AF and energy information from OAM, EIF indicates NSACF to adjust maximum number of UEs and PDU sessions for energy saving in slice.

Details regarding the procedures and impacts to existing services, entities and interfaces are available in the above mentioned documents.

ETSI Contributions

A work item (WI) was proposed by the EXIGENCE project partner in ETSI ISG, namely, permissioned distributed ledger (PDL) for studying Energy Consumption Data Sharing based on PDL Service [13] (cf. Proposal 1, 2 & 3). This WI is studying: 1) existing methods for fine-grained EC metering in physical and virtual environments; 2) PDL service architecture enhancement for supporting E2E EC metering data collection; and, 3) distributed consensus mechanisms for EC metering data post-verification and service enforcement with smart contracts. An early draft documenting the work done so far in this WI is available [13]. Currently, fine-grained EC measurement approaches and techniques in 6G, metering infrastructure, prototypes, runtime monitoring, EC metrics, use cases and categorization of the services that impact EC are provided in the document. Challenges for enhancing the PDL service such as interoperability with diverse systems, especially, operating under different authorities, ensuring data integrity and trustworthiness in the absence of a unified governance model and scalability concerns with the increasing volume of metering data and how trust issues can be addressed during data sharing with PDL for supporting the E2E EC metering data collection are under discussion. For further details, please refer to [13].

IETF Contributions

Three energy related drafts were created in IETF [14] 1) draft-contreras-nmrg-green-intent-01 (cf. Proposal 2&3): It describes how customers can express their intents for green services from network providers and provides the necessary structure and attributes for such a green intent. It further describes lifecycle of green intent, its implementation and security aspects, 2) draft-stephan-green-use-cases-00 (cf. Proposal 3): It provides a set of use cases for energy efficient management of network devices like switches, routers and servers, and an early description of a framework to facilitate the exposure of energy consumption and 3) draft-contreras-pim-eco-mode-00 (cf. Proposal 2, 3 & 4): It proposes an extension to Internet Group Management Protocol (IGMP)/ Multicast Listener Discovery (MLD) messages to permit subscribers to indicate their willingness for applying eco-mode during distribution of media content.

To summarize, Table 1 maps the EXIGENCE Standards contributions to the proposals introduced in the "Way Forward" section and provides planned next steps. Finally, a detailed summary of the state-of-art analysis with regards to E2E energy measurements is available on the Green ICT Digest section of the Exigence website [7].

This section presented the measure-optimize-incentivize methodology of EXIGENCE and discussed the efforts and results from EXIGENCE [7].

Conclusion

This paper discusses importance of accurately measuring service-level EC and corresponding Greenhouse Gas emissions in ICT domain. Leveraging the most recent developments in mobile network area (5G Advanced) as an example, we highlight the complex nature of this task yet justify it through novel use cases, built-upon existing/imminent regulation, expected services, and importance of next generation mobile system (6G). By juxtaposing these to latest work in relevant standardization organizations, we identify necessary gaps and limitations of state-of-the-art. Accordingly, we present a novel approach advocated in European research project EXIGENCE under SNS JU framework. In particular, we discuss concrete, recent proposals and standardization contributions aimed to address the identified shortcomings.

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LJUPCO JORGUSESKI (ljupco.jorguseski@tno.nl) received the Dipl.-Ing. degree from the University Cyril and Methodius, Skopje, Republic of Macedonia, in 1996, and the Ph.D. degree from Aalborg University, Denmark, in 2008. From 1997 to 1999, he was an Applied Researcher at TU Delft, followed by a research position on wireless 3G/4G systems at KPN Research, The Netherlands, till 2003. Since 2003, he has been a Senior Consultant on wireless access at TNO, focusing on radio planning and (self-) optimization of wireless networks, and 3GPP and O-RAN Alliance standardization activities. He has co-authored over 30 publications in conferences, journals, book chapters, and patent applications.

EWOUT BRANDSMA (ewout.brandsma@tno.nl) received the Ir. degree in informatics from Twente University Technology, Enschede, The Netherlands, in 1986. For most of his career, he has been involved in industrial research (Philips, NXP) on a variety of topics, including massive parallel computing, information retrieval, and digital A/V entertainment. He has more than 20 years of experience in connected systems, most notably around the Internet-of-Things. Since 2024, he has been a Senior Scientist at TNO Networks, working on 5GA/6G networking technologies, green ICT (as part of EXIGENCE), and cellular wearables. He has participated in many EU-funded projects, was involved in standardization (DLNA), and has filed more than 35 patent applications.

DANIEL CORUJO (dcorujo@av.it.pt) received the Ph.D. degree in 2013. He is an Associate Professor at the University of Aveiro, Aveiro, Portugal, with Habilitation, and a Researcher from the Instituto de Telecomunicações, Aveiro. He has been researching in multiple areas around the intersection of telecommunications and computing fields, applied to different types of networks, architectures, and protocols. Lately, he has been involved in B5G/6G mobile network uptake for vertical digitalization and the development of energy-efficient mechanisms for ICT. He had authored over 120 SCOPUS-referenced papers, as well as standards within the IEEE and IETF, and participated in national/international research projects for more than 20 years.

ARTUR HECKER (artur.hecker@huawei.com) received the Dipl. Inform. degree from Universität Karlsruhe and the Ph.D. degree from ENST, Paris. He is the Director of Future Network Technologies and an expert at the Advanced Wireless Technology Laboratory, Huawei Munich Research Center. Since 2024, he has been a Deputy TM of the European research project EXIGENCE, dedicated to measured ecodata exchange pertaining to ICT service usage. Before joining Huawei in 2013, he was an Associate Professor at Télécom ParisTech, where he was leading the Security and Networking Research Group. Overall, he looks back at more than 20 years of entrepreneurial, academic, and industry experience in networks, systems, and system security.

LUIS M. CONTRERAS (luismiguel.contrerasmurillo@telefonica.com) received the M.Sc. degree in telecommunications from the Universidad Politécnica de Madrid in 1997, the joint M.Sc. degree in telematics from the Universidad Carlos III de Madrid and Universitat Politècnica de Catalunya in 2010, and the Ph.D. degree from the Universidad Carlos III de Madrid in 2021. In 1997, he joined Alcatel, working on Research and Development, standardization, product development and customer-engineering. In 2006, he joined the Network Planning Department at Orange. From 2002 to 2010, he was an Adjunct Lecturer at the Telematics Department, Universidad Carlos III. In 2011, he joined Telefónica, working on scalable networks, cloud, and distributed services, and is an active contributor in SDOs, like IETF, O-RAN, and ETSI.