Towards 6G-enabled Sustainable and Smart Mobility – A Vision and Roadmap

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***Abstract*—ICT and digitalization play a key role in the transition needed to fulfil the United Nations' sustainable development goals. In the case of the mobility and transport sector, sustainability challenges include not only reducing greenhouse gas emissions but also improving safety, accessibility, and resiliency of the transport systems. In this paper, we study how ICT, especially, the next generation 6G mobile communication technology can enable sustainable and smart mobility in the future. Our study focuses on three selected areas of mobility and transport, namely cars, ships, and drones. Unlike the existing works, we bundle up these three domains more comprehensively with that of 6G technologies and sustainability perspectives. We also provide a visionary roadmap on the most prominent technologies for 6G research to serve the future communication technology needs of sustainable and smart mobility.**

***Index Terms*—Autonomous vehicles, unmanned aerial vehicles, maritime autonomous surface ships, sustainability, technology forecasting, 6G.**

I. Introduction

All over the world, climate change is slowly driving efforts to change the way resources are used and waste is created and managed. Pollution is a major threat to our environment, and this is pushing societies to find a more sustainable usage of Earth's resources. The United Nations' (UN) sustainable development goals (SDGs) provide a blueprint for shared prosperity in a sustainable world by 2030 [1]. The UN SDGs aim not only to tackle climate change and pollution, but also to improve the sustainability of society with topics such as equality, inclusion, and safety. In Europe, the European Green Deal [2] aims to tackle climate change and environment related challenges and implement the UN SDGs. The goal is to have Europe as the first climate neutral continent by 2050. An intermediary goal has been set to 2030, at which the emissions should be cut by 55 % compared to 1990 levels.

Sustainable and smart mobility is a key element of the Green Deal. Given that transport accounts for a quarter of the EU's greenhouse gas (GHG) emissions, reducing GHG emissions is the key sustainability challenge of EU's strategy for sustainable and smart mobility [2], [3]. GHG emissions are not the only environmental costs related to mobility, however. Air, noise, and water pollution, but also accidents and road crashes, congestion, and biodiversity loss all affect health, wellbeing, and prospects. The EU's transport policy aims to ensure that the transport system is truly resilient against future crises as well. Furthermore, the transition towards sustainability includes the challenge that it must be done in such a way that it is just, fair, affordable, and available for all.

In this paper, we study how ICT, especially, the future 6G mobile communication technology [4] can enable sustainable and smart mobility in the future. ICT and digitalization will have a key role to play in the transition needed to fulfil the SDGs [5]–[7], and more specifically, to the transport modes. They will also drive the modernisation of the entire mobility and transport systems, making them seamless and more efficient. Sufficient wireless connectivity solutions, in particular, will be needed to implement the essential abilities such as sensing, navigation, and cooperation for smart transport entities. Therefore, in this paper, we mainly focus on discussing the wireless and mobile networks related aspects within the ICT umbrella of technologies [6]. Moreover, we focus studying three selected modes of mobility and transport, namely cooperative, connected, and automated mobility (CCAM), autonomous ships, and drones or unmanned aerial vehicles (UAV). Other relevant modes of transport, such as trains or airplanes, are left for future work. In this scope, we review the current state of the art of wireless connectivity solutions used in the selected transport systems and look into the visions towards 6G. We also establish a roadmap for the technology research and development. Finally, since many of the foreseen benefits of ICT and future 6G will require expansion of the communication networks and systems, we discuss the sustainability of ICT itself for a complete analysis.

The rest of the paper is organized as follows. Section II summarizes the related work. The sustainability opportunities brought by ICT for the selected transport modes are discussed in Section III, and the role of ICT and 6G in their future development in Section IV. The past and on-going research to improve the carbon footprint of ICT is discussed in Section V. Section VI presents a roadmap of technology developments and goals to be promoted in the future. Finally, conclusions are drawn in Section VII.

II. Related work and novelty

Different transport entities, such as cars, ships, and drones, have their own specialties in their specific transport missions. We observe that they, however, have some common objectives which include transportation of goods and people while improving autonomy and sustainability of the particular transport mission. Moreover, these objectives face also common

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challenges which include security (physical/cyber), prompt situational awareness, interoperability, and limited resources. To overcome these four challenges, the key mutual abilities of different transport entities are sensing, navigation, and cooperation. These abilities cannot be implemented efficiently without sufficient wireless connectivity solutions. The wireless communications using upcoming 6G technologies have been surveyed in several recent review papers including [4], [8]–[10]. Furthermore, current 6G initiatives around the world and their visions are summarized in [7]. In these papers, the consolidated effect of different transport entities had less attention. The marriage of transportation units and 5G/6G connectivity solutions have been surveyed by [11]–[17]. In these works, the sustainability issues were given less attention. Evaluation of sustainability effects have been surveyed in [6], [7], [18], [19]. It is concluded that a clear connection between sustainability factors and future communication technologies is crucial. However, the relationships of sustainability to different transportation units remain largely untouched. Finally, Table I briefly summarizes the existing survey papers related to the target topics. The major difference between this and existing surveys is that we bundle up the three domains of CCAM, ships and drones more comprehensively with that of 6G technologies and sustainability perspectives.

TABLE I
COMPARISON WITH PREVIOUSLY PUBLISHED REVIEWS AND SURVEYS. TRANSPORTATION MODES (TRANSPORT.) INCLUDE CCAM (C), SHIPS (S), AND DRONES (D), COMMUNICATION MODES (COMMUN.) INCLUDE 5G AND 6G, AND SUSTAINABILITY TOPICS (SUSTAIN.) INCLUDE ENERGY (E), MATERIAL (M), AND SOCIETAL (S).

Reference	**Transport.**			**Commun.**		**Sustain.**		
	C	S	D	5G	6G	E	M	S
[4], [8]–[10]					✓			
[11]	✓	✓	✓	✓	✓	✓		
[12], [17]	✓			✓	✓			
[22]	✓				✓			
[20]		✓						
[13]		✓		✓	✓			
[14]			✓	✓	✓			
[15], [16]			✓	✓				
[18]						✓	✓	
[19]				✓	✓	✓		
[6], [7]				✓	✓	✓	✓	✓
[21]				✓		✓	✓	✓
[23]	✓	✓	✓	✓	✓	✓		✓
This article	✓	✓	✓	✓	✓	✓	✓	✓

III. 'GREEN BY ICT' – MAKING MOBILITY AND TRANSPORT SYSTEMS MORE SUSTAINABLE

Sustainability in ICT is linked to the Green ICT concept [24]. There are two aspects to it, green by ICT, where ICT is used for sustainability, and green in ICT, to reduce the environmental impact of ICT. The current visions of the next generation 6G mobile technology are well in line with the Green ICT thinking. The 6G visions highlight sustainability as a key goal to reduce the environmental impact of expanding communication networks while further savings are expected from indirect and systemic impacts of 6G-enabled use cases. In its entirety, 6G aims to enable a large number of UN SDGs use cases, some of which are illustrated in Figure 1. Intelligent transport is one of them. In this section, we discuss how ICT and future 6G can be used to improve the sustainability of cars, ships, and drones/UAVs.

In green by ICT, one of the challenges is assessing the true scale of the effects of using ICT in terms of its environmental impacts [25] aka the enablement effect [21]. Various studies have led to a wide variety of results, due to the degrees of freedom in the assessment methodology, use cases, definition of the baseline, estimation of the environmental impact, etc. When looking at the impacts of ICT, one should not only focus on the direct impacts, in which ICT is part of both solutions, making more from less, and problems, resource consumption and waste generation [26]. Indirect and systemic impacts can bring much larger savings. One key issue is however the possibility of rebound effects [27]. They characterize the negative side effects of efficiency policies and strategies that ended up losing the environmental gains they had permitted. For example, growth in autonomous car sharing might be at the expense of public transport.

For the mobility and transport of people and goods, ICT solutions have been shown to contribute to optimizing transport, routing, and fuel usage, lowering congestion and air pollution, as well as improving safety. For cars, emissions can be reduced on several levels through driving dynamics, flow control, type of transport, departure time, or destination [28], [29]. Some fuel and CO2 reduction values based on literature reviews can be found in [29]. The driving support systems, the traffic management, routing, navigation, the emission zones and dynamic emission pricing, warning systems, platooning and sensor sharing, all contribute at the vehicle or traffic level to improve the sustainability. Likewise, in shipping, improved vessel routing, improved port and logistics infrastructure and operation, improved vessel health and status information, and supply chain transparency, all support the sustainability and greater autonomy of the transport mode [30]–[32]. Some estimates of the potential CO2 emissions reduction through operational measures can be found in [33]. In [34], the authors provide a comprehensive overview of the GHG emissions reduction potentials for maritime transport and measures published in literature. For UAVs, savings can be obtained via careful optimization of missions with regards to routes, trajectory, QoS, types and number of actions to be taken [35], [36]. The key aspect is the energy consumption and how to manage it to extend the lifespan of the UAV's mission. Furthermore, UAVs enable novel use of ICT for sustainability [35], [36]. UAVs can be used to enhance transport and logistics, industrial, automotive, and maritime systems. They can perform sensing and monitoring missions, provide data collection and on-demand edge computing services, and deliver packets and equipment in hard-to-reach locations. A concrete example is

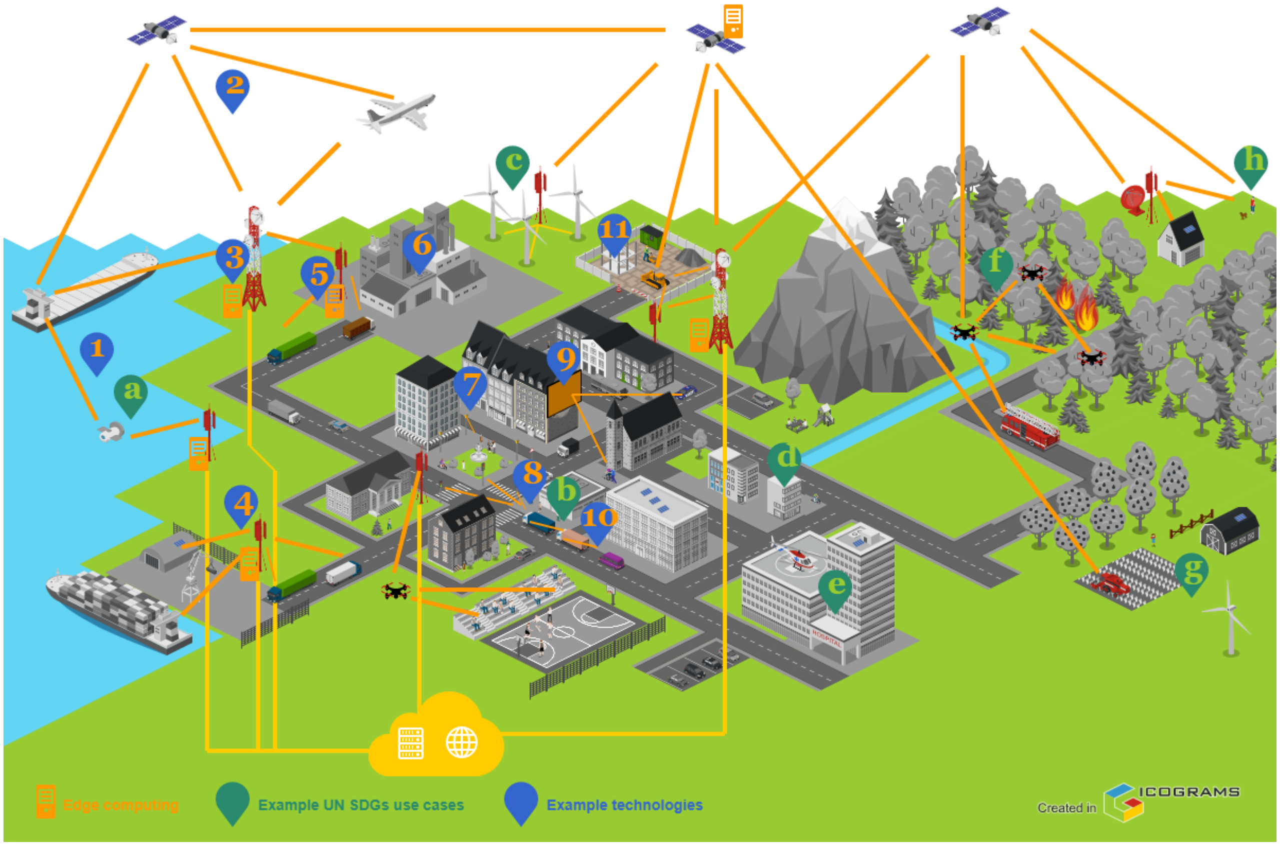

Fig. 1. Sustainability scenarios and key technologies of 6G. Example UN SDGs use cases: a) Life below water monitoring - b) Intelligent transport system - c) Resource management and monitoring (water, energy, etc.) - d) e-Learning - e) e-Health - f) Life on land monitoring - g) e-Agriculture - h) Universal access to the network. Example 6G technologies for smart mobility use cases: 1) Underwater communications - 2) 3D dynamic hybrid network - 3) AI/ML data fusion - 4) Edge computing/intelligence - 5) Cybersecurity - 6) Communication for harsh environments (e.g. industrial) - 7) VLC - 8) MIMO (cell-free communications, multiple access) - 9) Reconfigurable intelligent surfaces - 10) TeraHertz communication - 11) Integrated localization/sensing and communication.

that switching from in-person to drone inspections can reduce GHG emissions substantively while being faster and safer [28]. The last but not the least, the integrated logistics and transport system, improving the flows in freight transport, is seen as a key concept towards efficiency and sustainability in transport logistics [37].

The deployment of the ICT infrastructure and networks and the provision of enabling services and relevant content play an important role in reaching the SDGs. Capacity, coverage, latency, reliability and resilience, cybersecurity, and costs are key features of the connectivity solutions to support those goals. Connectivity is needed within the vehicle or vessel itself, e.g., for sensor data collection and control, between vehicles and towards the core network, where additional computation capabilities can be found and information can be further exchanged. This is essential to help with autonomous and sustainable decision making. We discuss the current state-of-the-art and 6G visions of the connectivity solutions in more detail in Section IV. Apart from the specific features of the communication network, other ICT aspects that need enhancements to reach the full benefits include: IoT systems, AI/ML algorithms and big data analytics, standardization (e.g., reporting and visualization), cloud computing (greater flexibility and share of information), and robotics and autonomy.

IV. ICT in Mobility and Transport Systems

Figure 1 depicts the overall vision of 6G for mobility and transport systems. It also gives examples of key future communication technologies to realize this vision. In this section, we introduce the current state-of-the-art and look at the requirements and visions towards 6G in the context of the car, ship and drone/UAV communications.

A. *Cooperative, connected, and automated driving*

The CCAM initiative by the EU aims to use new communication technologies in vehicles to improve road transport. These improvements range from reducing greenhouse gas emissions, increase road safety, and avoiding congested roads to prevent negative impacts on life, the economy, the environment, and the climate [38]. Modern vehicles facilitate a variety of onboard sensors to observe their environment, e.g., for obstacles, weather, or road conditions. In cooperative and connected driving, sensor information sharing between road participants and infrastructure increases perception capabilities of their environment [39].

1) Available communication technologies: In CCAM, there are two types of communication technology currently adopted by OEMs to support the vehicle to everything (V2X) communication. The first one is based on the IEEE 802.11p standard and primarily used for short-range broadcast messaging. Its European version is called ITS-G5. In the U.S., the technology is referred to as Dedicated Short Range Communication (DSRC) or Wireless Access in Vehicular Environment (WAVE). The second technology is specified by 3GPP and named cellular vehicle-to-everything (C-V2X). The specification includes support for the short-range via sidelink communication (i.e., the PC5 interface) and for the long-range, utilizing the LTE and 5G infrastructures (i.e., the Uu interface). The cellular technologies have some advantages for critical use cases due to the limitations of the 802.11p based ones [40].

So far, the C-V2X evolution path in 3GPP has advanced from LTE to 5G New Radio (NR). In Rel-14, C-V2X was designed to provide message transport for basic safety features and traffic efficiency. In Rel-15, enhanced V2X use cases, integrating 5G NR and LTE architecture into C-V2X, were defined, among others. Rel-16 focuses on advanced V2X services and QoS [41]. Vehicles can be connected to the network through gNB or eNodeB and can additionally utilise sidelink communication via LTE or NR independently from the radio technology of the serving cell. Additionally, concurrent connections to different RAT (E-UTRA, NR) over Uu interface or sidelink are possible to increase reliability [42].

2) Vision towards 6G: The next-generation network needs to support the growing number of autonomous vehicles along with new emerging services. Especially, more capacity, integration of distributed intelligence, energy efficiency (EE), and coverage needs to be pushed forward. The main reason to upgrade V2X is that current systems are unable to support fully automated vehicles or operations within high-density network conditions [43]. The emerging connected and automated vehicles will produce a large quantity of data inside the vehicle, but also the enabling system such as the wireless network acquires a large portion of that data. To achieve higher data rates in 6G-V2X sidelink communication has to be mmWave enabled and utilizing MIMO techniques to increase data rates and reliability. For special use cases requiring very high data rates in the magnitude of Tbps, Terahertz (THz) and Visible light communication (VLC) can help allocate more bandwidth in the unused spectrum to the road user [43]. Technological challenges such as high propagation loss need to be addressed to make THz or VLC a viable option. Yet, as pointed out in [17], higher data rates in direct communication do not solve the problem of more bandwidth needed in applications such as remote driving or cooperative driving. However, since the data is often only significant locally, finding ways to aggregate sensor data, e.g., through offloading to an edge computing server, will help to avoid congestion in the network and reduce the latencies and use of bandwidth. More computational power at the edge enables extensive AI/ML techniques involving security, high data rates, adaptive and intelligent decision making. Also the cellular network can use AI/ML to reliably assign resources and predict or estimate wireless channels in a highly mobile environment [22]. The future vision is to combine terrestrial with non-terrestrial communication networks (NTN) to cover also remote areas and will be essential for vehicles.

B. Autonomous ships

Unmanned shipping, or Maritime Autonomous Surface Ships (MASS) [44], is the future of the maritime industry by enabling cost-effective shipping [45]. From remote controlled to fully autonomous ships, the direct benefits include the redesign of spaces since the crew is not on-board and the more efficient use of the crew and their skills [46]. Indirect benefits include improved optimization of the operations, processes, and safety at sea. Autonomous operations require that measurements and decisions are performed with high reliability, fault-tolerance, and security/safety [13], [20]. Connectivity solutions inside and outside the ship are thus key enablers.

1) Available communication technologies: There are two types of technologies available for maritime communications [13], [47]: (a) those used for distress and safety-related communications, mandated by the International Maritime Organization (IMO) under the International Convention for the Safety of Life at Sea (SOLAS), and (b) commercially available systems, such as satellite solutions and terrestrial telephone and data networks.

SOLAS specifies the required communications infrastructure by the industry and authorities under the GMDSS (Global Maritime Distress and Safety System) for passenger and cargo ships on international waters. The set of required equipment depends on the intended routes of the ship. In addition to SOLAS systems, automatic identification system (AIS) transceivers, used by vessel traffic services (VTS), are installed on large ships. They can play the role of some of the compulsory elements of GMDSS. To provide more capacity, the international telecommunication union (ITU) has defined the VHF Data Exchange System (VDES) [48] and its satellite component has been introduced in the ITU radiocommunication sector (ITU-R) radio regulations at the 2019 world radio conference (WRC-19) [49].

Several commercial wireless technologies used to deliver voice and data connectivity to mobile users can be used in the maritime environment [47]. The connectivity systems available for navigation include eLoran, satellite data communications, cellular communications (4G, 5G, etc.), Wi-Fi, and short-range communications [13], [20], [47]. Underwater wireless communication can also be used [20], [50]. 3GPP, standardizing 5G and working on 5G-Advanced, has included maritime communications (MARCOM) in its use cases [51]. Those use cases are not targeting autonomy, but all other connectivity services, including on-board services, machine type communications, monitoring services, and safety related services. Additionally, interworking and harmonization are considered. Many of the other services covered by 3GPP are applicable to MARCOM [52]: mobile services, IoT, and satellite services as well as services specified for other verticals (e.g., public safety domain, automotive domain, factory automation domain, and satellite industrial domain).

2) Vision towards 6G: The IMO's Strategic Plan (2018-2023) has a key Strategic Direction to "Integrate new and advancing technologies in the regulatory framework" [53]. This includes the modernization of GMDSS, coming into force in 2024, for which VDES is seen as the most probable system [54]. For remote and autonomous shipping, the IMO has established a MASS working group within the maritime safety committee (MSC), which organised a regulatory scoping exercise (RSE) and prepares guidelines for MASS trials [44]. Increased automation's potential applications can also be seen in ports and include automated cranes, automated rubber-tyre port vehicles and automated intermodal connections [55]. Digitalization can enhance port resilience by enabling better collaboration and decision-making. Overall, one of the main drivers of digital transformation in the maritime transport sector is cost reduction [56]. Stricter environmental requirements in the maritime transport sector may also act as a driver for digital transformation. Compatibility, integration, and interoperability of ICT and systems are very important aspects, as much as digital security and data transparency. There is a need for real-time and secure data transfer throughout the whole supply chain, which is partly lacking cost-efficient and reliable communication means [31]. Varying data quality and its scattered locations are also obstacles for optimal utilization of data. Another aspect of wireless communications in ships is the possibility to replace cables by wireless connections [57]. Wireless technologies can also allow easy and cost effective retrofitting of older ships. However, the metallic environment, the watertight doors, and the noises can severely affect the wireless signal propagation, similarly to what can be experienced in industrial environments.

C. Drones

The drone/UAV market is in expansion and can be divided into consumer and commercial markets [14], [58]. UAVs can serve many purposes, e.g., monitoring, public safety, disaster recovery communications, etc. They are easily deployable and can offer better LOS visibility than terrestrial systems, thus offering better coverage. Here drones and UAVs are used interchangeably and unmanned aerial system (UAS) is used to refer to the UAV and the person controlling it.

1) Available communication technologies: UAVs need to have connectivity for 1) remote control or command and control and for 2) downloading the data from on board sensors such as video or pictures. For consumer and commercial drones, proprietary connectivity solutions have been used in addition to Wi-Fi based approaches. In addition, cellular systems may be able to offer more reliability and capacity for many commercial applications. Operators, industrial players, and research community have reported several successful tests using, e.g., commercial 4G networks [59], [74]. Those tests have shown that 4G can be used in beyond-visual-line-of-sight (BVLOS) scenarios.

A recent UAS standardization overview is given in [15]. There are many ongoing activities in 3GPP, IEEE, and ITU. The ITU is usually aligned with 3GPP. The UAV is included as a basic capability in terms of 5G service requirements [60]. The UAV communication requirements cover command and control (C2), uplink and downlink data to/from the UAV to the network, and the operation of radio access nodes on-board UAVs [61], [62]. The UAS traffic management (UTM) provides services to the UAV and its operations, including identification and tracking, authorization, enforcement, regulations of operations, and data storage. Authorized users may also obtain identity and metadata of the UAS. For instance, there are four types of C2 communication options. Direct C2 link or network-assisted C2 communications between the UAV and its remote controller can be employed when a human remote controls the UAV. Third option is to use UTM-navigated C2 communication allowing the UTM to maintain a link with the UAV in order to monitor its flight and provide information. This is especially relevant for automatic or (near) autonomous UAVs which might have been provided a flight plan but need to report flight information and receive updates or assisting information. Near autonomous flights (fourth option) are seen to require significantly smaller end-to-end communication latency than automatic flights. UAVs are also worked for in Rel-18 in terms of improving 5G capability of controlling UAVs and using, e.g., radio beam based interference mitigation approaches [63].

Some of the challenges in using cellular networks include, e.g., UTM, especially with an increasing number of UAVs, network coverage and base station deployment not being optimized for flying objects, interference to/from UAVs since UAVs are able to see more base stations due to their locations, and larger uplink capacity needs than regular UEs [4], [14], [16]. Because of challenging operating environments, it is good to use multiple redundant communication links in drone missions. Additionally, the UAV may play the role of relay or radio access node, which can limit the flight time of the UAV due to the limited battery capacity.

2) Vision towards 6G: The trend in UAV is towards long range and autonomous flight [15]. In this context, standardization is key to enable reliable wireless connectivity and improve safety by giving, e.g., the possibility to take control of a misbehaving UAV or providing safety commands for avoiding collisions in unexpected situations. UAVs are being used for such diverse missions that they require diverse connectivity solutions. Depending on the application, latency and throughput capacity can be have crucial effects to the success of a mission. Swarm applications are also envisaged to play an increasing role in, e.g., monitoring and surveying, emergency and disaster management, and search and rescue [64]. For swarms, connectivity has additional requirements, of which communication reliability and network and interference coordination and management are key issues. UAVs are an important part of the dynamic heterogeneous 3D network vision as they can provide local solutions for various communication needs [11].

V. 'Green in ICT' – Making ICT More Sustainable

The use of ICT is expanding in the mobility and transport systems, as well as in general, and it is thus important to ensure that the ICT itself will also become more sustainable. In 2015, the ICT sector represented 1.4 % of the total carbon footprint of society and it is expected to be reduced by 50 % by 2030 [7]. EE of communication systems has improved throughout the years, but challenges to be solved still exist, even if this trend is expected to continue [7], [65].

A life cycle assessment (LCA) is an important tool to assess the potential environment impacts of a product or a service over its whole life cycle [21], [66]. For ICT, the major impacts are caused by resource consumption and waste creation. Resource consumption includes energy and material. To lower the environmental impact of the energy consumption, either renewable energy sources are used, or the consumption is reduced through EE solutions. To reduce the material costs, the hardware utilization must be improved, the overall cost of wireless network deployment must be significantly reduced, and novel architecture and key technologies for wireless network virtualization need to be further developed [8]. Challenges include inconsistent standards, low compatibility, and complex adaptation. The other major challenge of green in ICT is e-waste and circular economy. The ICT community is working towards creating metrics to be incorporated throughout the ICT technical domains to improve the design and life cycle management of products and services [67]. Important circular aspects to consider are longevity, reparability, and upgradability/modularity/reusability [66]. Many KPIs exist to assess decarbonization of networks and standardization organisations (ITU-T, ETSI, 3GPP, etc.) are working on efficiency aspects of ICT equipment and services, circular economy, monitoring and measurement methods, etc. [68], [69].

EE and sustainability are fundamental pillars of the 6G development. In 6G, the spectrum efficiency will improve but at the same time network and device EE need to increase drastically compared to 5G networks due to the network densification and the increasing number of connected devices [11], [70]. Many solutions are already in use in 5G [21], e.g., sleep modes. Energy harvesting technologies enabling devices to become self-sustained are envisioned in 6G, using novel technologies such as reconfigurable intelligent surfaces (RIS), backscatter communication, or symbiotic radio [71]. Network side infrastructures will be supplied by renewable energy sources. Edge computing will allow offloading of data for processing, which will increase devices' battery-life. By providing processing power close to end users, their devices do not need that processing capability, which can help decrease e-waste. Automation and AI/ML solutions are key elements to drive the trade-offs in network configuration and management towards more EE deployments. Softwarization, disaggregation and increased granularity of the network components will increase flexibility and reusability. Predicting devices' activity and mobility using AI/ML solutions will also help network management and power saving. Other promising techniques to increase the sustainability of 6G include VLC, cell-free networks, aerial RANs, and integrated sensing and communication, [8], [9], [19], [28].

UAVs can play an important role in greening ICT [35], [36]. When they are used as aerial base stations, they can help in reducing energy use and pollution, and enhancing the connectivity, battery life and QoS of e.g. IoT devices. They can also reduce the need to build extra network infrastructures for, e.g., mission critical missions, and hence save resources.

VI. Roadmap and Opportunities

Even if the applications and use cases of cars, ships and drones differ, they have many common needs for connectivity solutions. 6G will improve current 5G performance for all KPIs [11], [23] and will hence further help in the modernization, digitalization, automation, and more generally the usage and sustainability of all transport modes. Even before 6G, the 5G-Advanced, starting from 3GPP Rel-18, will bring enhancements to 5G on many aspects, including energy efficiency and uplink performance [63]. In this section, we present R&D&I opportunities and a roadmap for the area.

Based on the extensive literature survey, conducted for this paper, we were able to identify a set of key 6G technologies and opportunities for the three modes of transport. We also analyzed the maturity levels of the different technologies. Figure 2 summarizes the results. Other 6G technologies not included in the figure include, e.g., coding and modulation, mmWave communications, full duplex systems, etc.

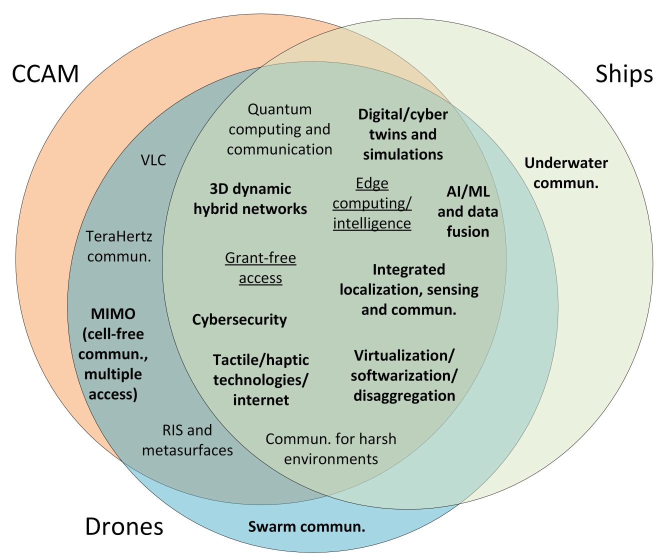

Fig. 2. A Venn diagram of 6G technologies and opportunities for vehicles, ships, and drones. The technology maturity levels are loosely defined and indicated as: research / **some availability in a specific sector** / available but not yet fully optimized.

Due to limited space, we are able to discuss only some common highlights here to be considered in the future research and development. One key common enabler for vehicles, ships and drones will be to extend the network coverage both in space and time [9] to provide seamless coverage and

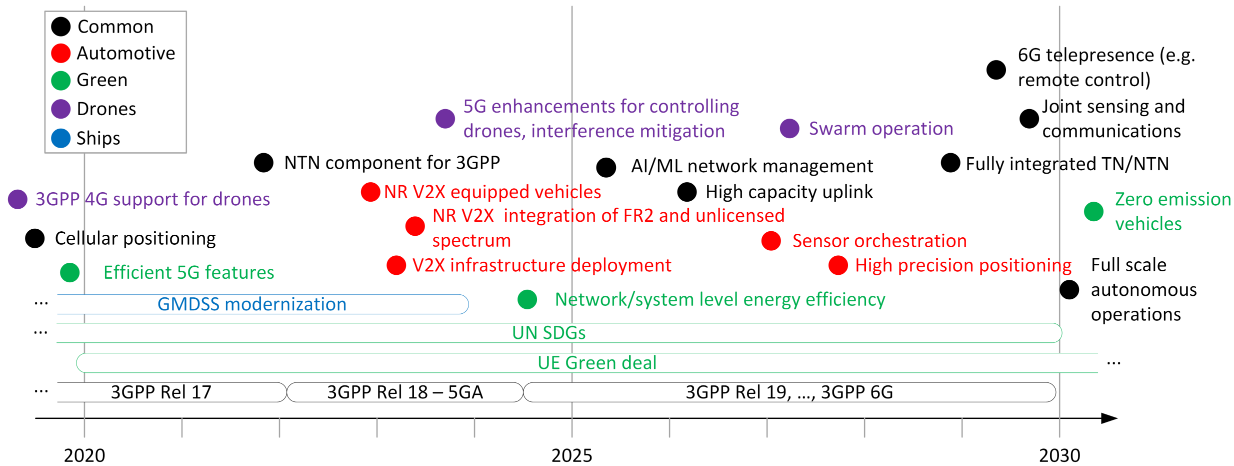

Fig. 3. Future communication technology roadmap for low-carbon and smart mobility solutions for cars, ships and drones.

always-on network access worldwide via aerospace-ground-ocean integrated information networks, also referred to as 3D dynamic hybrid networks [8], [11], [23]. Mobility and hence the dynamic aspect of the connectivity solution for the end user is very important in the transport domain. This will require efficient solutions for the configuration and management of future networks, which can be enabled by network softwarization, mobile cloudification, and data mining and AI/ML technologies [72], [73]. Furthermore, exploiting edge computing for optimizing, e.g., energy consumption or service end-to-end delay will be important for all the transport domains [23], [72]. Data mining and AI/ML solutions can be used to help minimize energy consumption, manage throughput prediction, and improve network security for the mobility and transport applications [11]. Finally, cybersecurity is a major component in all communication links and the hybridization and softwarization of networks brings new challenges [8], [23], [72].

In order to put things into a timeline, we drafted a roadmap of the technology development and standardization. The roadmap is depicted in Figure 3 and it covers the technology developments towards the year 2030, when 6G is expected to become commercially available. The roadmap includes technologies that are common for all of the studied transport modes, sustainability aspects, as well as technologies that are transport mode specific. The figure uses colour-coding to highlight the different use cases.

VII. Conclusions

In this paper, we studied how ICT and especially the next generation 6G mobile technology can help to enable sustainable and smart mobility in the future. Although the different transport entities analyzed, that is, cars, ships, and drones, have their own specialties, we observe that they have some common objectives, such as transportation of goods and people while improving autonomy and sustainability of the transport missions. Therefore, the entities face also common challenges, and to overcome them, the key mutual abilities of the transport entities are sensing, navigation, and cooperation. These abilities cannot be implemented efficiently without sufficient wireless connectivity solutions. While solutions exist to some use cases with sufficient quality, we identified several research directions where more efficient 6G connectivity can provide significant added value for the end users of the different transport domains. Among others, we emphasize especially the potentiality of 3D hybrid networks and distributed way of computing, network control, and learning. The findings reported in this paper are based on an extensive literature survey, and they provide a better understanding on the future opportunities of 6G for sustainable and smart mobility. The results can be used as a basis for more detailed studies in the different topic areas, as well as for directing R&D&I efforts in related academia, industry, public sector, and regulation.

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