Boosting Short-Range Wireless Communications in Entities: the 6G-SHINE Vision

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***Abstract*—In the coming 6th Generation (6G) era, the pervasiveness of wireless communications in everyday life and vertical markets is expected to take a major leap, enabling revolutionary and highly demanding use cases. In-X subnetworks are expected to be located at the edge of the 6G 'network of networks'; they can provide short-range high-performance wireless connectivity in entities like robots, industrial production modules, vehicles, classrooms, etc., overcoming the limitation of current wireless technologies in terms of data rate, latency, complexity, and reliability. In this paper, we present the vision of the 6G SHort range extreme communication IN Entities (6G-SHINE) project, granted by the Smart Network and Services Joint Undertaking (SNS JU). 6G-SHINE is the first project exclusively focused on short-range in-X subnetworks, and aims at providing a significant breakthrough in multiple wireless communication fields, from physical layer to network architectures. We present the main project objectives and provide an overview of the technology components being researched. Also, we discuss the expected long-term beneficial impact of the project and its potential for future 6G standardization.**

I. Introduction

The 6th Generation (6G) radio access architecture is expected to take the form of a 'network of networks', integrating subnetworks with diverse capabilities in terms of supported services, complexity, communication range, and operational spectra. It will seamlessly combine or interconnect macro/micro/pico networks with non-terrestrial networks (NTN), networks of drones as well as both private and campus networks [1].

In-X subnetworks are short-range low power radio cells, located at the edge of the 6G 'network of networks', to provide highly localized and high-performance wireless connectivity. They can be installed in entities like robots, production modules, vehicles, and classrooms, with the aim of replacing wired infrastructure for those communication services whose requirements in terms of data rate, complexity, latency, and reliability, cannot be supported by existing radio technologies, including the 5th Generation (5G) radio [2]. For example, industrial subnetworks can support fast closed-loop robot control applications with a fraction of ms control cycles and reliability beyond six nines; in-vehicle subnetworks can replace Controller Area Network (CAN) bus and automotive Ethernet for braking, engine control, Advanced Driver Assistance Systems (ADAS); in-classroom subnetworks can be used for immersive extended reality (XR)-based education programs. Since some of the services supported by in-X subnetworks can be life-critical, subnetworks must be able to operate in a standalone manner similarly to *ad hoc* networks; still, they can benefit from a connection with a 6G parent network, which can aid radio resource management, operation monitoring, traffic steering, management of computational resources, as well as provide a unified authorization/authentication framework.

The concept of subnetworks addresses use case 5 (Dynamic and trusted local connectivity zones) defined in the ITU vision for the future development of International Mobile Telecommunications (IMT) for 2020 and beyond [3], and is also included in the European vision for the 6G Network Ecosystem [4].

The 6G SHort range extreme communication INside Entities (6G-SHINE) project, selected by the Smart Network and Services Joint Undertaking (SNS JU) in their first call of proposals launched in January 2022, aims at pioneering the main technology components for in-X subnetworks. 6G-SHINE is the first project exclusively focused on short-range communication in a 6G context, and has the ambition of opening up the wireless option for a plethora of demanding services and applications, by providing significant advances with respect to 5G and existing short-range wireless solutions. In this paper, we present the 6G-SHINE objectives and the envisioned technology components, ranging from physical layer enablers up to architectures and relationship with the 6G 'network of networks' paradigm. A discussion on the envisioned long-term societal and economic impact of the project is also presented.

II. Main project objectives

The 6G-SHINE project aims at pioneering the main technology components for in-X subnetworks. Our research leverages specific characteristics of in-X installations, such as short-range communication, devices in a static position or in predictive motion, spatial correlation of large-scale radio

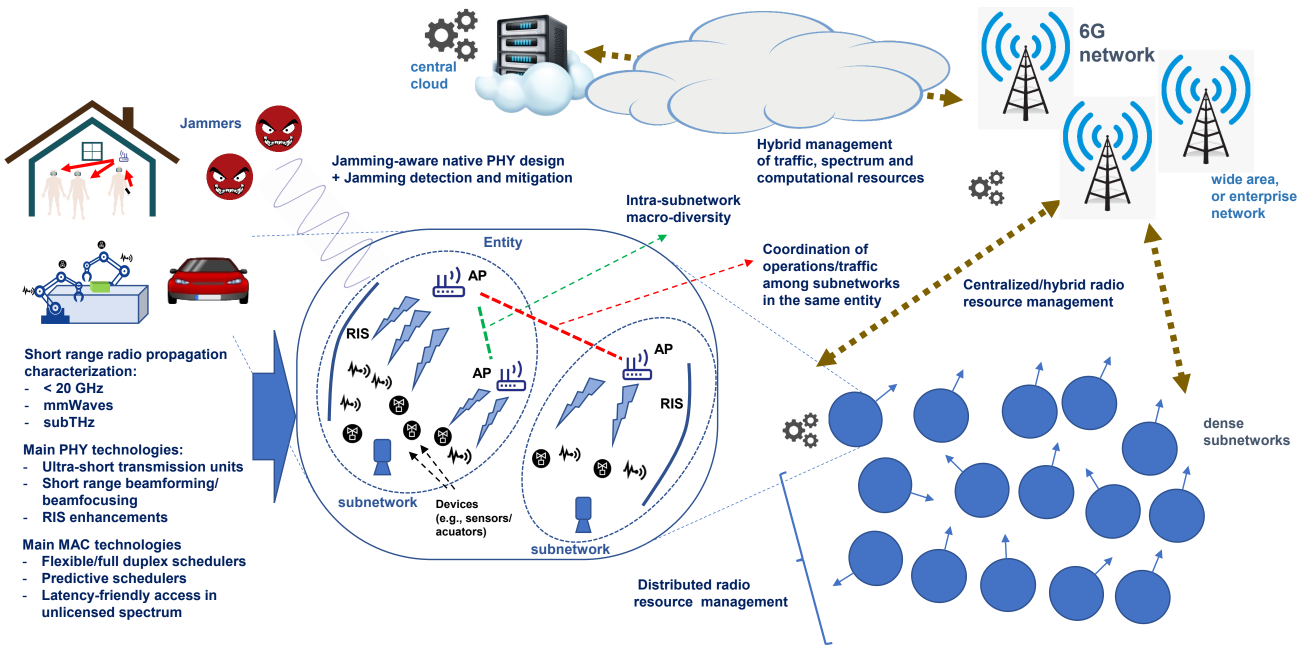

Fig. 1. Envisioned 6G-SHINE technology components.

parameters, and the ability to partially control the propagation environment. Additionally, the research explores the connection between in-X subnetworks and the broader 6G infrastructure to achieve a high-performance and cost-effective design. Subnetworks may operate over different spectra, i.e. cmWave, mmWave, and sub-THz bands [5]. Also, both licensed and unlicensed spectrum options are to be pursued for subnetworks. Licensed bands may provide an interference-controlled carrier at the cost of a licensing fee; they can eventually be used for static installations, (e.g., in a factory), but their usage for mobile subnetworks (e.g., subnetworks installed in vehicles) might require roaming agreements across regions. On the other hand, unlicensed bands ease service continuity across borders but require tailored measures to deal with uncontrolled interference generated by other systems operating in the same frequencies. In general, the usage of licensed or unlicensed bands is highly dependent on the use case and the purpose for which the subnetworks are deployed.

The main objectives of the 6G-SHINE project can be summarized as follows:

- Define relevant application scenarios, use cases, and architectures for in-X subnetworks, and analyze related performance requirements;
- Characterize the radio propagation channel in the short-range scenarios and frequency bands of interest, considering cmWave, mmWave, and sub-THz regions of the electromagnetic spectrum;
- Design new physical layer and medium access control enablers for scalable requirements in terms of latency, reliability, energy efficiency, complexity, or data rate, leveraging the opportunities offered by short-range subnetworks;
- Develop cost-effective radio resource management techniques in dense dynamic subnetwork crowds, considering both legitimate and malicious interferers. The project will explore fully distributed solutions, where subnetworks perform their decisions independently, as well as centrally coordinated and hybrid approaches, where a 6G parent network can aid operations of subnetworks in its coverage area;
- Develop new methods for the integration of subnetworks in the 6G architecture and efficient orchestration of radio and computational resources among in-X subnetworks and the 6G ‘network of networks’.

The project will result in a portfolio of new technological solutions for wireless short-range communication, whose performance will be verified via simulations and – for selected components – via laboratory demonstrations. In this respect, the project targets a technology readiness level (TRL) in the range 2-4 [6]. It is worth mentioning that the integration of the technology components in a subnetwork prototype is not an objective of 6G-SHINE, and will be pursued by future research.

III. Envisioned Scenarios and Technologies

6G-SHINE is expected to advance the state-of-the-art in several wireless communication fields, ranging from radio propagation to architectural enhancements. A pictorial overview of the 6G-SHINE technologies, and their interconnection, is shown in Figure 1. A subnetwork may consist of one or more access points (APs), which may be equipped with embedded edge controller capabilities, serving multiple devices. Such devices can be low-cost sensors/actuators, but also cameras, wearables, and XR devices. Multiple subnetworks can be installed inside a given entity like a production module, a vehicle, or a classroom. Subnetworks can spontaneously become very dense, such as those installed in vehicles on a congested road, thereby necessitating intelligent mechanisms to efficiently manage interference. Also, subnetworks can be assisted in their decision-making by a parent 6G network, which can provide support in managing traffic, computational resources, and spectrum allocation.

The main scenarios and envisioned technologies are concisely presented in the following.

A. Scenarios and use cases.

We have identified three major categories of use cases for in-X subnetworks: industrial, in-vehicle, and consumer. Currently, a significant effort is committed by the project partners in defining applications where in-X subnetworks can bring significant benefits, and analyzing related performance requirements in terms of data rate, latency, cycle time, reliability, and synchronicity.

For industrial subnetworks, possible use cases are robot control (e.g., multi-axis control, force control), visual inspection cells, unit test production cells, and collaborative robots (including swarms of automated guided vehicles). Such use cases may require communication cycles in the order of a fraction of ms, and link reliability similar to wired communications, e.g., six nines and beyond. Also, collaborative operations of robots manipulating raw items within the same industrial facility demand high synchronicity with jitter below 1 μs.

In-vehicle subnetworks will leverage modern zonal Electrical and Electronic (E/E) architectures in vehicles, where Electronic Control Units (ECUs) are installed in each zone of the vehicle, grouping the control functionalities at a given physical location, and are connected to a central high-performance computing unit (HPCU) acting as a central brain [7]. Subnetworks can replace parts of cabling connections of sensors with an ECU, or between ECUs and the HPCU. A subnetwork installed in proximity of an ECU may need to support different traffic types, such as low data rate powertrain control traffic with bounded latencies, and high data rate uncompressed video with strict reliability and timing from ADAS sensors.

For consumer subnetworks, various use cases have also been identified. In-classroom subnetworks can be used for immersive experiences via XR; an education session can be entirely remote, with students and instructors participating from home and interacting with a virtual environment, or hybrid with part of the students in the class and others joining remotely. Devices can be handhelds, wearables, smart glasses, motion sensors, as well as ambient sensors distributed in the subnetwork area. The media to be shared include telepresence type of footage to allow interactive participation of remote students (or teachers). Besides education, other relevant consumer applications for subnetworks are interactive gaming and entertainment. Such applications may require Gbps data rates, and low latencies in the order of a few ms. Also, energy efficiency is of great importance here for the sake of minimizing size and weight of the devices.

6G-SHINE will analyze functional and performance requirements for these categories of use cases, also based on -when possible- data traffic analysis in real or emulated scenarios. Additionally, 6G-SHINE will study short-range radio propagation characteristics in the identified scenarios for multiple frequency bands, ranging from cmWave to sub-THz spectra. So far, the standardization activities for channel models by 3GPP and ETSI has mainly focused on scenarios such as urban, suburban, indoor office, and recently indoor factory [8]. However, the characterization of short-range links at these frequency bands has been generally overlooked, especially for industrial and in-vehicle scenarios. We aim at filling this gap by conducting channel measurements and developing novel channel models suitable for the performance analysis and coverage planning for the scenarios of interest.

B. Physical layer solutions.

The fulfillment of demanding communication requirements subsumes an enhanced physical layer design, which is able to harvest the advantageous short-range characteristics for high performance at a low cost. 5G has already introduced features such as mini-slots and large subcarrier spacings on an orthogonal frequency division multiplexing (OFDM) air interface for the sake of supporting latencies below 1 ms [9]. 6G-SHINE will move one step forward by supporting communication intervals below 100 μs. Such short intervals call for novel approaches for efficiently multiplexing data and reference sequences needed for enabling channel estimation for coherent demodulation, such that detection quality can be kept with a reasonable reference signal overhead. Also, new fast retransmission mechanisms (possibly including new control and feedback channel techniques) should be designed for delivering stringent reliability and latency targets, while maintaining high spectral efficiency.

Dense deployments of in-X subnetworks call for directive transmissions, which are introduced with beamforming capabilities. Particularly at high carrier frequencies, it becomes possible to build an electrically large antenna array at an access point (AP) with a small form factor, easing the implementation of high-gain beamforming. Our research will also leverage near-field propagation characteristics in subnetworks for steering beams not only in the angular domain but also in the depth domain (i.e., beamfocusing), therefore reducing intra-beam interference for devices located at the same angular direction but different distances [10]. The introduction of metasurface-based antennas can provide a low-cost hybrid analog-digital implementation of electrically large antennas by moving part of the signal processing tasks at the electromagnetic level as well as for significantly reducing the latency for initial beamforming and the signaling overhead [11], [12].

When operating at sub-THz frequencies, power efficiency is a key concern. Traditional CMOS technology becomes less efficient compared to compound III-V semiconductor devices like InP [13]. New power models covering radio-frequency front-end, analog and digital baseband processing, and digital-to-analog/analog-to-digital converters are to be developed for assessing the power consumption for different beamforming architectures, in the view of a low power and low latency physical layer design.

Also, the support of life-critical services calls for a physical layer that is natively robust to potential jamming attacks, as well as from interference from other radio systems operating over the same band. This may be realized via the introduction of a large number of parallel data paths, whose time and frequency allocation can be optimized for providing the required robustness while keeping a reasonably low energy consumption, and without significantly affecting spectral efficiency.

As mentioned above, a subnetwork may feature multiple APs. These APs can be used for serving different groups of devices, but also for providing redundant links for the same devices; this can improve communication reliability by counteracting the effects of blockage due to, e.g., metallic obstructors in a production cell, or engine parts in a vehicle. As a nearly-passive alternative to macro-diversity, reconfigurable intelligent surfaces (RISs) can be installed in a classroom, in the proximity of a production module, or even inside a vehicle, for easing reflections and steering useful signal power in a desired direction [14]. Effective usage of RISs in subnetworks also subsumes new efficient methods for acquiring the channel state information needed for configuring the reflecting elements, as well as capabilities of suppressing parasitic reflections.

C. Medium access control solutions.

Subnetworks may need to multiplex services and applications having very diverse requirements. For example, a subnetwork controlling robot operations can support different cycle times for each group of sensors and actuator couples; a control network inside a vehicle may need to multiplex low data rate control commands with high data rate video feeds from ADAS sensors. We postulate that the usage of in-band full duplexing (where an AP can transmit and receive simultaneously over the same band), and flexible duplexing (where transmit and receive operations can happen simultaneously over different subbands in the same operational carrier) can ease the support of services requiring different uplink/downlink switching points in the same subnetwork [16]. The usage of flexible/full duplexing can be made possible by the recent advances in self-interference cancellation, as well as by the expected low transmit power in in-X subnetworks. 6G-SHINE will then pursue novel flexible and full duplexing scheduling solutions, where resources are allocated on the basis of the traffic characteristics and the position or mutual coupling of the devices, for the sake of reducing cross-link interference originating from simultaneous uplink and downlink transmissions.

As mentioned in section III.B, subnetworks can be equipped with multiple APs, but only one of these APs may have edge controller capabilities; this raises the need of using other APs (or devices) as relays toward the AP with controller capabilities. In this respect, 6G-SHINE will design novel multi-link solutions where different data forwarding methods among devices and APs (including coded cooperation [15]) will be analyzed and optimized for the specific in-X deployments. It is worth mentioning that the usage of multi-link diversity might be particularly important for high carrier frequencies, given their higher sensitivity to blockage.

Further, 6G-SHINE aims to develop novel medium access control solutions for devices within the subnetworks that are using a RIS to improve wireless connectivity. Devices within a subnetwork can be classified in categories with respect to their traffic characteristics, mobility, likelihood/frequency of usage of RIS, and the medium access control solution can be prescribed based on the category.

Also, efficient support of traffic flows with different characteristics may require predictive scheduling solutions. 6G-SHINE will leverage service/application-domain information of the specific use cases to predict the amount of required radio resources in the near future. This includes the possibility of exploiting context information (e.g., video feeds by ADAS sensors, movements of a robot arm) to anticipate the activation patterns of devices and identify features relevant for managing traffic flows. Such predictive scheduling mechanisms will exploit online learning techniques to continuously evaluate the context-based generation of traffic and dynamically adapt scheduling decisions. This has the potential of significantly reducing the amount of signalling overhead for resource allocation.

Since in-X subnetworks may also operate over unlicensed spectra, novel medium access mechanisms other than well-known carrier sense multiple access (CSMA) with exponential back-off are to be pursued [17]. This is because the listen-before-talk approach of CSMA schemes, in current regulations, clashes with the need of supporting deterministic communication cycles or dependable communication with guaranteed latencies. 6G-SHINE will investigate medium access solutions based on clear channel assessment (CCA) slots of different durations, support for prioritizing time sensitive traffic over best effort traffic, spread spectrum and power adaptation that will ensure fair access to the unlicensed spectrum without compromising latency. The long-term objective is to propose novel coexistence mechanisms for deterministic communication in the unlicensed spectrum, to impact future radio regulations.

D. Radio resource management.

The location of in-X subnetworks is likely uncontrolled, they can be mobile and can spontaneously become very dense. The capability of dynamically managing radio resources for counteracting harsh and time-varying interference is therefore of paramount importance for achieving the expected communication requirements. Our assumption is that, in order to achieve the expected performance in dense scenarios, subnetworks must be able to autonomously select their transmission mode, encompassing frequency subband, transmit power, and beamforming weight. 6G-SHINE will then investigate fully distributed solutions, where subnetwork decisions on transmission mode are based on local sensing only, and eventually, some limited side information exchanged with its neighbors. In case subnetworks are in the coverage area of a parent 6G network (e.g., an enterprise or a wide area network), the latter can aid the management of radio resources. We will then study centralized solutions where a central controller collects sensing information obtained by subnetworks in its coverage area. Centralized solutions are expected to improve spectral efficiency with respect to fully distributed approaches thanks to the more comprehensive environment visibility at a central node; on the other hand, centralized solutions have poor scalability and might be costly in terms of signalling overhead, especially for mobile subnetworks where information on the perceived radio conditions need to be reported to the central controller at a fast pace for performing timely decisions.

Moreover, in a practical scenario, only part of the subnetworks might be able to communicate with the central controller, as others might encounter disadvantageous channel conditions. This may occur, for example, for in-vehicle subnetworks driving in a tunnel, or mobile robots whose communication link with an enterprise 6G network is shadowed by a large machinery. Hybrid solutions will then also be pursued, where the parent network can aid decisions on the transmission mode of each subnetwork, based on limited available information such as subnetwork density, noisy positioning estimates, or channel state information of only a fraction of the subnetworks [18]. For example, the 6G parent network can limit its contribution to recommending policies to be used locally at each subnetwork, rather than specific actions; or it can assign spectrum resources at a coarse granularity, while local decisions can further optimize resource allocation. The solution space will include heuristic techniques such as graph coloring, and simulated annealing, but also modern machine learning methods based on multi-agent reinforcement learning, and graph neural networks. Machine learning solutions have the promise of reducing the amount of information needed for performing efficient decisions, provided the decision model is trained for the environment of interest. A promising approach for the hybrid framework is federated learning, where models trained locally at each subnetwork can be aggregated in a central agent and re-distributed to the individual subnetworks [19].

Besides the management of interference generated by other subnetworks, 6G-SHINE research will also focus on solutions for managing interference from jammers as well as from other technologies operating in the same spectrum. While physical layer design is meant to provide a tier of protection against external attacks, further detection and mitigation mechanisms are needed for supporting life-critical services. In this respect, we will explore solutions based on autoencoders and reinforcement learning.

E. Management of traffic, spectrum, and computational resources.

Subnetworks can handle different traffic flows, with diverse priorities and levels of criticality. It is our assumption that time-critical traffic requiring, e.g., sub-ms latencies, stays within a local subnetwork and that the corresponding application's computation tasks happen there too. Accordingly, less critical applications allow flows being forwarded to an edge cloud processor, or even to a central cloud, thus offloading the computational load of the subnetwork. Also, certain entities (e.g., vehicles, classrooms) can have multiple subnetworks installed, where computational capabilities might not be equally distributed, such that a given response might only be performed by a specific AP. 6G-SHINE will investigate methods for traffic steering and computational offloading among subnetworks in the same entity and between subnetworks and the parent network. The tradeoffs of each offloading policy will be identified and their impact on control and user planes will be studied. The subnetwork APs can have flexible roles in coordinating and combining communication links while giving the option for certain devices to offload a specific task to other devices if needed [20]. Efficient multi-hop schemes, also involving devices in the subnetwork, will then be devised. This hybrid role, which enables each node to mimic selected responsibilities of both a device and an AP at the same time, can result in novel distributed network architectures. Also, novel architectural enhancements and interfaces are needed in order to connect the subnetwork with the broader 6G 'network of networks', and allow subnetworks to benefit from 6G capabilities in terms of authentication/authorization policies. Furthermore, the parent network plays a crucial role in managing spectrum allocation at a higher hierarchical level compared to the radio resource management units. This includes coordinating spectrum sharing not only among different subnetworks but also with other radio systems. Additionally, the parent network can facilitate spectrum sharing between the subnetworks and the broader 6G network, ensuring efficient and optimized spectrum utilization across the entire network infrastructure.

IV. Expected Impact

6G-SHINE will result in a portfolio of novel technological enhancements for short-range communication, some of which will be brought into standardization. Since 6G standardization will start after the conclusion of the project (expected in August 2025), the 6G-SHINE will mainly focus on pre-standardization. Besides 3GPP, relevant standardization bodies targeted by the project partners include ITU, ETSI, IEEE (802.11, 802.15), along with industry fora such as 5G-ACIA and 5G-AA. 6G-SHINE aims at contributing to the development of study items on low-power short-range networks with inputs from the designed physical layer and medium access control enablers and a clear consideration of vertical needs (e.g., dependable service levels).

Possible technology components with standardization potential include channel models and test specifications for short-range links, beam-based communication for constrained devices, RIS-enabled smart repeaters, and signaling procedures for flexible/full duplex enabled scheduling. Also, 6G-SHINE aims at raising discussions on spectrum possibilities for future short-range communication, in the light of potential new allocated bands, and novel regulation mechanisms for ensuring deterministic low latency communication in the unlicensed spectrum. Besides, 6G-SHINE will contribute to the definition of the 6G 'network of networks' architecture, by delivering novel interfaces and enhancements for in-X subnetworks. Architecture research may also contribute to the development on new concepts related to disaggregation of radio access technologies, as envisioned by the O-RAN Alliance [21].

In the long term, we expect 6G-SHINE technology components to be effectively integrated and implemented in entities like robots, vehicles, production modules, classrooms, etc. This will empower vertical and consumer domains with capabilities superior to those by 5G, and ensure their seamless integration with 6G parent networks.

In-X subnetworks can bring wireless to a pervasiveness level never experienced earlier. By providing deterministic performance, subnetworks can reduce cable harness, translating to lower capital and operational expenditures, higher flexibility in the installations, and improved environmental footprint. Lower cable harness also translates to lower equipment weight, and therefore lower fuel consumption and carbon emissions in e.g., vehicles. The usage of immersive extended reality applications can enhance significantly the quality and attractiveness of educational programs, making them more inclusive.

V. Conclusions

In this paper, we have presented the vision of the SNS JU 6G-SHINE project, aiming at developing novel technologies for short-range communication, with a focus on in-X subnetworks and their integration into the 6G 'network of networks'. In-X subnetworks can revolutionize wireless communication capabilities for industrial, vehicular, and consumer entities. They can offer a wireless solution that surpasses the limitations of existing radio technologies, eliminating the need for extensive cabling even in life-critical applications. This advancement would not only enhance flexibility and mobility, but would also bring unprecedented convenience and efficiency to a wide range of sectors. Our research is focused on low technology readiness levels (TRL) and will result in a portfolio of technology components encompassing the physical layer, medium access control, management of radio and computational resources, and architectural enablers. We have concisely introduced the main envisioned technologies that aim at boosting short-range communication capabilities, such as beamforming/beamfocusing, reconfigurable intelligent surfaces, flexible/full duplexing and predictive schedulers, hybrid interference management, and multi-link enhancements. Finally, we have discussed the expected long-term impact of the project, including standardization aspects.

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