STATE OF MOBILE NETWORK EVOLUTION

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Executive Summary

Mobile communications is a rapidly evolving field that encompasses various technologies, applications, and services. The main drivers of this evolution are the increasing demand for high-speed data, low-latency connectivity, ubiquitous coverage, and enhanced user experience. This white paper builds upon our previous work, "Mobile Communications Towards 2030" which was issued in November 2022 and summarizes new national and regional initiatives on 6G, along with exploring three promising technological building blocks: Full Duplex, Joint Communication and Sensing (JCAS), and Intelligent Surfaces.

Chapter 1 provides an overview and update of the following national and regional initiatives: NSF Resilient & Intelligent NextG Systems (RINGS) in the U.S., TETRA in Canada, ATIS NGA in North America, as well as activities in China, Japan, Europe (Hexa X and Hexa X II, Germany, Finland), and Korea. Recent noteworthy events are additionally described, including the CHIPS and Science Act, the National Science Foundation (NSF) and National Security Council (NSC) workshop on 6G and the NSC document "principles of 6G", the U.S. "national standards strategy for critical and emerging technology" approach, and the U.S.-EU Trade and Technology Council (TTC) and its 6G expert workshop.

Chapter 2 discusses Full Duplex, beginning with static and dynamic Time Division Duplex (TDD) and introduces the first step of Sub-Band Full Duplex (SBFD) using non-overlapping uplink and downlink sub-bands at the base station. It covers the evolution of duplex mode at the base station and wireless devices, design goals and challenges, technology enablers and enhancement areas, as well as the 3GPP study on duplex evolution in 5G-Advanced and the path to 6G.

Chapter 3 explores JCAS, which extends the network capability from "listen-and-talk" to "see-and-feel" and enables the network to leverage its resources and support new services. The section covers motivation, use cases and applications, as well as the evolution of positioning, joint communications and sensing, design goals and challenges, and technology enablers and enhancement areas.

Finally, Chapter 4 examines intelligent surfaces, which are used to manipulate the propagation environment and improve the effective wireless channel between the transmitter and receiver. The section covers motivation, use cases, a comparison of intelligent surfaces with existing topology solutions, and addresses design goals and challenges, and technology enablers for intelligent surfaces.

1. State of Mobile Network Evolution - Initiatives toward 6G

1.1 Overview of premier national and regional initiatives

There are many national and regional 6G activities happening throughout the world. These initiatives are broadly covered in "Mobile Communications Towards 2030" in greater detail, but we are providing an update and summaries of some of the premiere 6G initiatives below.[1]

1.1.1 U.S. NSF RINGS

NSF, Office of the Under Secretary of Defense, Research & Engineering (OUSD R&E), National Institute of Standards and Technology (NIST), and nine industry partners have partnered to develop the RINGS program[2] to accelerate research in areas with significant impact on emerging NextG wireless and mobile communication, networking, sensing, and computing systems, along with global-scale services. The goal of the RINGS program is to approach the design of NextG network systems by considering resilience as the primary concern while aiming for superior performance. The program will be instrumental for enhancing the security and reliability of the NextG systems, while advancing the underlying technologies that will support stringent communication and computational performance demands that are expected of such networks over the next two decades. The 37 winning proposals were announced by NSF in April 2022.[3]

1.1.2 Canada Digital Equity Grid Innovation initiative

Mitacs is a non-profit organization supporting Canadian innovation by connecting industry and academia. Mitacs launched its new Digital Equity Grid Innovation initiative, in partnership with VMware, to "advance applied research that will play a critical role in paving a sustainable path to 6G". A new research and innovation center has been established in Montreal, in partnership with the IEEE Future Networks Initiative. The center will develop "infrastructure that bridges technologies from the satellite, wireless, networks and cloud industries".[4]

1.1.3 ATIS NGA

In 2020, the ATIS formed the "Next G Alliance" to advance North American mobile technology leadership over the next decade through private sector-led efforts. Its primary objective is to influence North American government and research communities. With a strong emphasis on technology commercialization, the work will encompass the full lifecycle of research and development, manufacturing, standardization, and market-readiness.

The foundational goals of the Next G Alliance include providing North American 6G market leadership, spanning the full range from R&D, manufacturing, standardization, and market-readiness. This is achieved by developing a Next G National Agenda, creating a North American Model for Success, and identifying strategies to reach 6G Market Leadership.

The Next G Alliance drives actions across a broad range of areas including policy, funding, research priorities and core technology development areas. It brings together diverse segments of the industry and leading research institutions, premised on the notion that research should be leveraged early to ultimately create a pathway to product realization and commercialization.

1.1.4 China 6G Efforts

China officially launched research and development for its 6G mobile networks in 2019.[5] The Ministry of Science and Technology (MOST) set up two working groups. The first group consists of government agencies responsible for promoting 6G research and development. The second group consists of vendors, operators, and Chinese research agencies and universities. Their purpose is to form a panel tasked with laying out the development of 6G and proving its scientific feasibility.

In addition, MOST granted 15 research projects on 6G under the framework of "national key R&D project" (2020).

The IMT-2030 (6G) Promotion Group was established in 2019 by the Ministry of Industry and Information Technology (MIIT).[6] The members include major Chinese operators, vendors, universities and research institutions. The promotion group supports China's industry and university research and development toward 6G.

Other 6G research activities from China include the launch of a test satellite operating in the THz band (2020).

1.1.5 Japan 6G Efforts

The Ministry of Internal Affairs and Communications (MIC) established the Beyond 5G Promotion Consortium[7] and Beyond 5G New Business Strategy Center in 2020.[8] The former is the core organization to promote the strategy among industry, academia, and government, accelerating various initiatives, and promoting international collaboration. The New Business Strategy Center is meant to accelerate securing intellectual properties by the Japanese players and promote global standardization strategically.

Several activities have followed, including white papers, such as from NICT (National Institute of Information and Communications Technology).[9] In November 2021, the Japanese government and Beyond 5G Promotion Consortium hosted an international conference where the stakeholders presented and discussed their views on Beyond 5G/6G research, technologies, and international cooperation.

1.1.6 Europe 6G Efforts

EU-level activities

Like earlier generations, a main part of the collaborative research efforts within Europe is done on EU-level within the *Horizon 2020* and follow-up *Horizon Europe* research frameworks. Within the context of future mobile networks, the main effort has been, and is, within the *Hexa X*[10] and *Hexa X II*[11] projects.

Hexa X was launched in 2021 and has focused on the foundation of future mobile networks by developing 6G visions and use cases, investigating the corresponding requirements and capabilities, and studying key candidate technologies to realize these capabilities.

As of 2023, the Hexa X project is nearing its completion and it is being succeeded by the Hexa X II project. Hexa X II will build on the results of the Hexa X project and go from basic research toward systemization and early validation, including proof-of-concept, of the concepts and technologies developed within Hexa X.

Hexa X II includes 44 partners including major manufacturers from Europe, North America and Asia.

National-level activities

In addition to the EU-level activities, extensive collaborative work on future mobile networks is also carried out on a national level in many European countries.

As an example, the German Federal Ministry of Education and Research is funding several projects including *6G-ANNA* [12]and the *Platform for Future Communication Technologies*.[13]

Another example is the 6G Flagship initiative[14] led by the university of Oulu.

1.1.7 Korea Efforts

South Korea's Ministry of Science and ICT plans to commercialize an initial 6G network service in 2028, two years earlier than its initial schedule.

The government of Korea's strategy for 6G consists of preemptive development of next-generation technologies, securing standard and high value-added patents, and laying R&D and industry foundations. The government of Korea reportedly expects to invest a total of KRW 200 billion (U.S. $169 million) between 2021 and 2026 period to secure basic 6G technology.

The government will encourage local companies to produce 6G materials and equipment and develop open RAN. The government plans to secure leadership in standards and to develop Artificial Intelligence (AI)-based cloud native core

network technology built on South Korean AI chips and to test launch its first low-orbit communication satellite in 2027.[15]

The Electronics and Telecommunications Research Institute (ETRI) announced a new, collaborative research project with the University of Oulu in Finland to develop an advanced system architecture for as-yet-unstandardized "6G" systems. The collaboration, which is part of the 6G Bridge program. The project started in July 2021 and is expected to last until June 2024.

Samsung also opened an Advanced Communications Research Center in Seoul to focus on 6G in early 2019. Samsung and LG Electronics are investing $800 million in setting up research centers in Seoul, South Korea.

1.2 Going forward

At the time of writing in June of 2023, it appears too early to gauge the progress of the various initiatives. The major regional and country efforts are expected to continue, and possibly expand in the coming years.

At the global level, ITU-R is expected to begin work on performance requirements and evaluation criteria for IMT 2030 in early and late 2024, respectively.[16] It is expected that 3GPP Release 20 will begin to study 6G/IMT 2030 items.

In the U.S., the CHIPS and Science Act[17] which aims at strengthening the semiconductor industry, has several parts that benefit wireless research. They include the Technology, Innovation and Partnerships (TIP) directorate under NSF, which has wireless research among its priorities.[18] Recently, TIP issued a "dear colleague letter" requesting inputs from potential industry and government agency partners to support "innovations to enhance the various aspects of next-generation communications, sensing, networking, and computing systems".[19]

Other relevant parts of CHIPS include the Public Wireless Supply Chain Innovation Fund, with the focus to "drive wireless innovation, foster competition, and strengthen supply chain resilience".[20] Also relevant is the Microelectronics Commons, which aims to create a "path to faster lab-to-fab production and strengthen American microelectronics development and production capacity" and includes 5G/6G among its priorities.[21]

Beyond research, the U.S. government has recognized 6G and mobile in general as critical technology. In April 2023, the NSC and NSF organized a workshop on 6G. Following the workshop, NSC issued the document "Principles for 6G: OPEN & RESILIENT BY DESIGN" with six principles addressing these topics[22]:

- Trusted Technology and Protective of National Security
- Open and Interoperable Innovation
- Secure, Resilient, and Protective of Privacy
- Affordable, Environmentally Sustainable, and Globally Connected
- Spectrum, Novel Materials, Manufacturing
- Standards & International Collaborations

In addition, the U.S. government is increasing its attention on standards and issued the national standards strategy for critical and emerging technology in May 2023, with Communication and Networking Technologies featured first among eight focus area in total.[23]

The report notes that the U.S. has lagged in participation in ITU but expects a change with the election of the U.S. candidate as secretary-general. The report identifies an action to work with the private sector to educate and train a new standards workforce.

At the transatlantic level, the U.S. and EU launched the TTC in 2021, with the objective "to promote U.S. and EU competitiveness and prosperity and the spread of democratic, market-oriented values by increasing transatlantic trade and investment in products and services of emerging technology, strengthening our technological and industrial leadership, boosting innovation, and protecting and promoting critical and emerging technologies and infrastructure."[24] Of particular interest is Working Group 4 which focuses on information and communications technology and services, security and competitiveness.

A 6G expert workshop was held in April 2023, and included three panels: introduction and scene setter; use case categories and technology visions; and key enablers. Workshop recommendations on mechanisms for trans-Atlantic collaboration on 6G will be provided to the fourth TTC meeting in Sweden 30-31 May 2023.

The B7 is a group of business associations from the G7 countries (e.g., the U.S. delegation is led by the U.S. Chamber of Commerce). A B7 meeting was held in Tokyo in April 2023, and issued its recommendations to the G7 political leaders.[25] Under the digital transformation goals, 6G is highlighted as an emerging critical technology, and there was a recommendation to promote research collaboration among the G7 members' initiatives.

2. Advances in the Evolution of Full Duplex Communication[26]

2.1 Motivation, deployment scenarios and use cases for duplex evolution

In a TDD band, the spectrum is shared between UL (uplink) and DL (downlink) in time domain based on a specific pattern. Almost all existing (LTE and NR) TDD network deployments are currently limited to DDDSU (three downlink subframes, one special transition subframe, and one uplink subframe) UL-DL frame structure resulting in an approximately fixed 4:1 DL:UL ratio. There are drawbacks with this semi-static TDD, which include limited UL transmission opportunities that lead to low UL duty cycle and impact on UL latency. For example, an UL packet arriving at the first DL slot will be blocked for five slots till the first UL slot arrives. Dynamic TDD DFFFU (where F is a flexible slot) enables efficient and flexible use of the time resources to improve the spectral efficiency of the wireless network. However, it suffers from cross-link interference between gNBs and UEs. Full duplex technology goes even further beyond dynamic TDD, by assuming simultaneous downlink and uplink within the same frequency band within a node. This includes simultaneous DL TX (transmit) and UL RX (receive) at the network side, along with simultaneous DL RX and UL TX at the device side.

Assuming frequency full duplex is very challenging, especially for high TX power deployments, due to large isolation requirements to handle the self-interference that occurs in addition to the cross-link interference present for dynamic TDD. SBFD using non-overlapping UL and DL sub-bands at gNB while the UEs are still operating in half-duplex mode is a first step for NR duplex evolution toward full duplex. In NR Release 18, 3GPP is studying the feasibility, deployment scenario and benefits for enabling SBFD at gNB. For example, in-band n78 (3.5GHz) with 100 MHz NR channel bandwidth, the SBFD UL sub-band is located in the center 20 MHz portion and DL sub-bands are allocated to each 40 MHz left/right for DL transmission in full duplex and still protects the adjacent channels from UL-DL interference.

SBFD improves latency in the following two aspects:

- Reduce UL latency by having UL opportunity in every slot improve UL duty cycle (Figure 1).
- Reduce DL retransmission latency, where the PDSCH A/N can be sent at an earlier opportunity (Figure 2).

Figure 1. Improved UL latency with SBFD (Source:5G Americas member company).

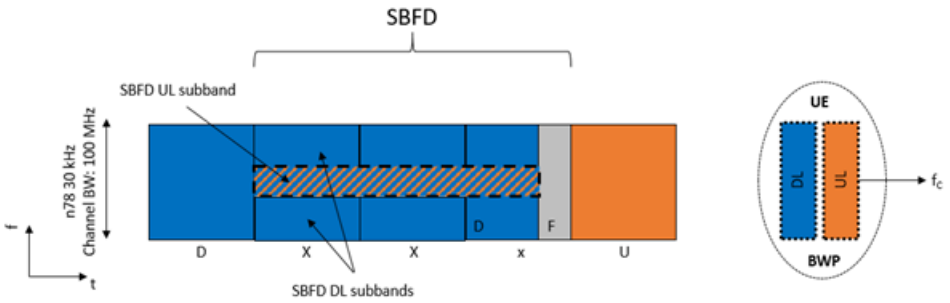
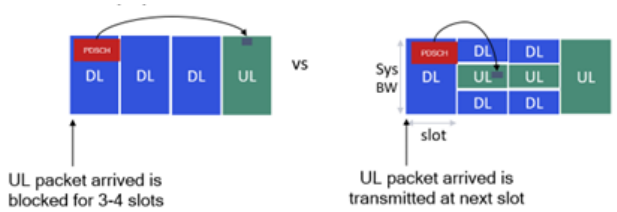


Figure 2. Reduced DL retransmission latency and UL queueing delay with SBFD (Source: 5G Americas member company).



SBFD also improves UL coverage by enabling UL transmission, such as in physical UL channels repetitions in UL sub-band across multiple consecutive SBFD slots. This will enable cell edge UE transmitting with maximum power and improving UL SINR.

Regarding the interaction between SBFD and legacy bandwidth part configuration, the uplink and downlink sub-bands in SBFD slots are separately configured from the legacy UL and DL bandwidth parts configurations in non-SBFD slots. It is a commonly understood that the configured UL/DL sub-band for SBFD should be confined within the configured UL/DL bandwidth part for a UE.

2.2 Evolution of duplex mode at base station and wireless devices

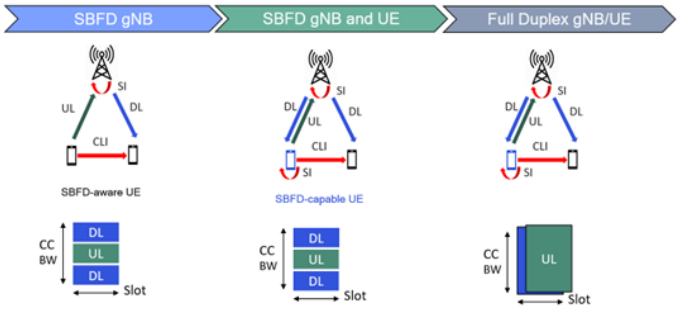
Non-overlapping SBFD operation only at the gNB is the first step toward leveraging all benefits of full duplex technology. Full duplex operation at the gNB can be done in a transparent manner, such as with legacy devices, or in a non-transparent manner. To enable SBFD operation in a transparent way, the full duplex slot is indicated as a 'flexible' resource to the legacy UEs to enable dynamic UL or DL scheduling in the slot. Non-transparent SBFD can be supported by creating a new UE category (SBFD-aware UE) that is indicated by the SBFD time and frequency pattern.

With the knowledge of the UL/DL sub-bands for SBFD-aware UE, some benefits can be leveraged. For example, the UE can utilize the SB knowledge to enhance the receiver filters and reduce impact of inter-UE cross-link interference (CLI). In addition, further power savings benefits can be leveraged where the UE can reduce the sampling frequency based on the available resource for DL/UL. In addition, some enhancement for the resource allocation and power control for UL transmission and DL receptions in the SBFD slots and TDD slots leveraging the different frequency resources and the difference in link quality due to existence of extra interference sources in the SBFD slots.

However, with SBFD operation at the gNB and HD operation at the UE, the latency reduction benefits are not fully utilized. Full utilization requires a SBFD-capable UE, such as a UE-side SBFD. Full duplex operation at the UE could be possible for some form factor where there is enough real state to enable separate panels or antennas, e.g., laptop or CPE specially optimized for higher band operation where UE can leverage two antenna panels and two different beams for simultaneous UL and DL, like in FR2-1.

In future NR releases, fully flexible full duplex, e.g., partial or fully overlapping UL/DL sub-bands at gNB (like FR2-1), and/or the UE could be the last step to leverage full advantages of spectrum utilization, latency reduction, coverage improvement, and scheduling flexibility.

Figure 3. full duplex evolution roadmap (Source: 5G Americas member company).



2.3 Design goals and challenges for full duplex communication

There are many challenges to enabling full duplex technology. The first major challenge is the self-interference mitigation at the full duplex node. For SBFD gNB, although DL and UL are separated in different sub-bands with a narrow guard band in between each DL and UL sub-bands, direct leakage may cause blocking or saturation of the gNB RF receiver and/or reduce the dynamic range. Additionally, the unwanted emissions caused by Tx may non-linearly jam the reception of the UL in the UL sub-band and reduce the SINR. In addition to the direct leakage, clutter echo from nearby reflectors may be of comparable signal strengths to the direct leakage and cause similar effects of blocking and jamming.

gNB side self-interference cancellation (SIC) capability for full duplex operation can be realized through a combination of solutions. For example, the gNB can use Tx/Rx antenna isolation, beam steering, analog and/or digital pre-distortion, digital interference cancellation, and analog and/or digital filtering solutions. For SBFD operation in FR1, Tx/Rx antenna isolation can be achieved by using one

TDD antenna panel for Tx and another panel for Rx during simultaneous full duplex transmission and reception, or a TDD antenna panel is split with additional isolation during simultaneous transmission and reception provided by a passive RF barrier. In FR2-1 where multiple antenna panels are available, some can be used for Tx and the remaining panels for Rx. It can be expected that antenna isolation achievable in FR2-1 is higher than for FR1. Beam steering can further improve isolation between Tx and Rx ports of the antenna or antenna panels during full duplex operation.

Analog and/or digital pre-distortion and digital interference cancellation can remove a significant amount of interference between the Tx DL sub-band(s) and the Rx UL sub-band in the gNB implementation. Analog and/or digital filtering solutions can further increase the isolation between the SBFD sub-bands and increase dynamic range and reduce in-band blocking during gNB reception. It can be expected that the combination of solutions which is best suited for a particular implementation depends on the base station class, the form factor, the supported frequency range, and co-siting considerations for the deployment.

For example, the gNB side full duplex implementation for a local area base station characterized by small transmit power and reduced Rx sensitivity can already achieve a significant amount of isolation during full duplex operation by relying on antenna isolation alone. Wide area base stations characterized by much higher transmit power and higher Rx sensitivity may need to implement a more extensive set of solutions to support full duplex operation.

The other challenge is the CLI between gNBs and between UEs. This includes interference between the gNB in the different sites and the gNB-gNB interference in co-sited multiple sectors deployment. In addition, co-existence with legacy operation is another major challenge. The co-existence refers to both co-channel (intra-operator) with legacy (TDD) gNB and legacy UE that are not aware of full duplex gNB and also adjacent-channel (inter-operator) co-existence.

2.4 Technology enablers and enhancement areas for full duplex at wireless nodes

The management of various types of interference, such as self-interference at the duplex nodes and cross-link interference between gNBs and between UEs requires both implementation and standard solutions. To handle self-interference, implementation-based techniques can be leveraged. For example, direct leaked self-interference may be handled by having separate Tx/Rx panels that improves spatial isolation, frequency separation by having UL and DL in separate sub-bands and means of interference digital or analog cancellation. Sub-band filters can be additionally used to mitigate the blocking effects. The clutter reflection can be mitigated by means of Tx and Rx beamform nulling and proper selection of Tx/Rx beam pairs. The Evolution to SBFD for NR has been made possible by advent of massive Multiple-In Multiple-Out (mMIMO) with NR and integrated high-power electronics, i.e., high-power high-density TRX/RFFE on MIMO panels; would not have been possible with LTE and traditional antenna structures such as those used in the low spectrum bands.

In addition, some enhancement existing 3GPP techniques may need to handle the CLI between the nodes. For example, the exiting inter-UE CLI and inter-gNB RIM framework may be extended to spatial domain to optimize the beam selection between UEs and gNBs and expanded to L1/L2 inter-UE CLI framework to increase flexibility and reduce reporting latency compared to Rel-16 L3 based inter-UE CLI framework. DL power allocation & UL power control may need to be enhanced for better handling of self-interference (SI) and CLI. Tx/Rx timing alignment at the full duplex node could be another aspect for special treatment. In addition, gNBs can exchange configuration of measurement resources for inter-gNB and/or inter-UE CLI measurement between cells.

2.5 3GPP study on 5G-Advanced duplex evolution and path to 6G duplex evolution

3GPP is studying in Release-18 the evolution of NR duplexing through full duplex operation at gNB in TDD band using non-overlapping UL and DL sub-bands while the UEs are still operating in half-duplex mode. The study started in RAN1 WG in May 2021 and expected be completed by August 2023 (RAN1) and December 2023 (RAN4).

A system-level study is undergoing to evaluate the benefits in terms of UL coverage enhancement, latency reduction and DL/UL UPT improvement backward compatibility. The study considers many deployment scenarios for both FR1 and FR2-1 bands, covering isolated single operator and co-existence scenario in the same and adjacent channels. In parallel, the RAN1 study considers the potential benefits of SBFD schemes and the possible enhancement from a RAN1 specification point of view. The RAN4 study is focusing on the RF feasibility of SBFD gNB for different base station classes (wide area, medium area and local area), co-existence with legacy operation, in addition to possible enhancement of RF requirements at the gNB and any

regulatory aspects for deployment SBFD in TDD band.

Based on the study conclusion, it is expected that 3GPP will have a work item in Rel-19 (starting in Q1 or Q2/2024) for SBFD operation at the gNB. In addition, another study item in Rel-19 or Rel-20 to study the feasibility of SBFD-capable UE and possible extension of gNB SBFD operation to overlapping UL/DL sub-bands.

3. Joint Communications and Sensing (JCAS)

3.1 Motivation, use cases and applications for JCAS

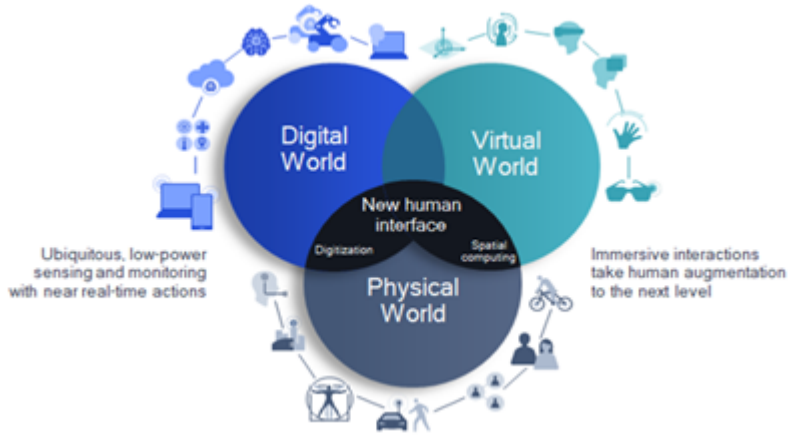
On a high level, JCAS can be defined as integrating the functionalities of communication and sensing into the same system or network. Communications and sensing share many commonalities in terms of hardware, signal processing, and spectrum. In this way, sensing functionality can be introduced as a service with a low incremental cost as it leverages on equipment and spectrum anyway deployed for communication purposes.

The integration of sensing and communication with JCAS could be at different levels, from loosely coupled to fully integrated, from shared spectrum, shared hardware, to shared signal processing module and network protocol stacks, and even using the same waveform for both communications and sensing, benefiting one another.

Overall, JCAS can extend the capability of a cellular network from “listen and talk” to “see and feel”. From the device perspective, they can sense their surroundings, and exchange their sensing results through communication links. From the network perspective, the widely deployed base stations for legacy cellular service could be re-used for wide area seamless RF sensing. In addition, combining the AI, communications, positioning and sensing capabilities, the cellular network could intelligently fuse the physical world with digital world and provide a variety of new services for consumers and industry customers.

A key benefit of JCAS, compared to the deployment of a system dedicated to sensing only, is that sensing capabilities can be introduced at a low incremental cost in a network already deployed for communication. This is like how early mobile broadband capabilities were introduced into systems already deployed for voice services or how support for IoT services are introduced into systems already deployed for mobile broadband.

Figure 4. Merging of physical, digital and virtual worlds (Source: 5G Americas member company).



During the transition stage from 5G-Advanced to 6G pre-research, there is significant interest in the new JCAS technology within both academic and industrial sectors. In particular, the 3GPP Release-19 SA1 study on integrated sensing and communications[27] has listed example use cases such as intruder detection in smart home or surroundings of smart home, pedestrian and animal intrusion detection on a highway, railway intrusion detection, rainfall monitoring, or sensing for flooding in smart cities.

Additionally, sensing for automotive maneuvering and navigation, vehicle sensing for ADAS, sensing at crossroads with/without obstacle, sensing for parking space determination, UAVs/vehicles/pedestrians detection near Smart Grid equipment, and

AGV detection and tracking in factories is included. Moreover, UAV flight trajectory tracing, network assisted sensing to avoid UAV collision, sensing for UAV intrusion detection, sensing for tourist spot traffic management, contactless sleep monitoring service, health monitoring at home, gesture recognition for application navigation and immersive interaction are all additional areas of focus for this study.

3.2 Evolution from positioning to JCAS

3GPP Release-16 introduced multiple NR UE positioning technologies, including methods based on time difference of arrival (TDOA) measurements, round-trip time (RTT) measurements with multiple base stations (Multi-RTT), and angle of arrival (AoA) or Angle of Departure (AoD) measurements. NR positioning reference signals (PRS) are defined to improve the performance of the NR positioning technologies.

In Release 17, positioning enhancements have been identified to address not only various coverage scenarios, but also higher accuracy, lower latency location, high integrity and reliability requirements resulting from new applications and industry verticals for 5G. Given the current market needs and expanding requirements, 3GPP Release-18 further expands and improves NR positioning with following work items: sidelink positioning solutions to meet V2X and public safety requirements and also expanding into commercial and IIoT use cases, wideband PRS for high accuracy positioning based on intra-band carrier aggregation, NR carrier phase positioning for high accuracy positioning, positioning integrity for mission critical use cases, and enhancements on RedCap UE positioning.

Within the 5G life cycle, the standardization of 5G NR UE positioning is promising to facilitate low-cost and fast deployment of cellular-based RF sensing. From an air interface design point of view, the spec impact on both the upper layer and PHY/MAC layer could be minimized, which means many of the network architecture designs, signaling, PHY layer reference signals and PHY layer procedures could be re-used for 5G RF sensing. Therefore, the deployment of the 5G positioning will lay a solid foundation for the further expansion into the 5G RF sensing.

Moving to 6G, JCAS that includes RF sensing could be designed with fundamental innovations on the network architecture and physical layer technologies, such as new waveforms. However, it is still reasonable to jointly design the positioning and sensing techniques under a common framework as a starting point. Additional studies on 6G will continue to investigate more use cases for JCAS, where sensing and communications could each improve the efficiency of the other.

3.3 Design goals and challenges for JCAS networks

From a communication perspective, the typical performance metrics include spectrum/energy efficiency, capacity, reliability, and latency. From a sensing perspective, the typical performance metrics include detection metrics (detection probability and false alarm rate), estimation metrics (mean squared error (MSE) and Cramer-Rao Bound (CRB)) and recognition metrics (recognition accuracy). However, it is still an open research problem to define a unified metric to evaluate the performance of JCAS systems. The design goals of JCAS systems depend on use cases. Particularly, 3GPP Release 19 SA1 study on JCAS has defined the RF sensing performance key performance indicators (KPIs) per use cases [35]. For example, below are the KPIs defined for the use case of intruder detection in surroundings of smart home.

Compared with typical radar sensing scenarios, the cellular based RF sensing has some unique technique challenges. Firstly, the strong self-interference due to limited space between Tx and Rx antennas/antenna panels, which may require advanced receiver algorithms for interference cancellation. The strong self-interference makes the detection of static or low speed targets very challenging, since they share the same property of close to zero in Doppler domain. Secondly, the reduced transmission power limits the maximum sensing range, especially for UE based RF sensing. Compared with UE positioning, the strong self-interference, the round-trip propagation path loss, and the loss due to reflections makes the link budget in sensing even more challenging. Thirdly, the rich clutter could degrade the sensing performance severely, as the antennas are pointing toward the ground in most use cases. The receiver's capability of clutter rejection plays a central role for high accuracy and robust RF sensing in the time-varying and multipath rich cellular environments.

Table 1. Performance requirements of sensing results for pedestrian/animal intrusion detection [35]

Sensing service area	Confidence level [%]	Accuracy of positioning estimate by sensing (for a target confidence level)		Accuracy of velocity estimate by sensing (for a target confidence level)	
		Horizontal [m]	Vertical [m]	Horizontal [m/s]	Vertical [m/s]
Outdoor (Highway)	95	≤1	N/A	N/A	N/A

Sensing resolution		Max sensing service latency [ms]	Refreshing rate [s]	Missed detection [%]	False alarm [%]
Range resolution [m]	Velocity resolution (hoz./vert.) [m/s x m/s]				
N/A	N/A	≤5000	≤0.1	≤5	≤5

3.4 Technology enablers and enhancement areas for JCAS

Integrating sensing into 5G/6G networks provides excellent opportunities for RF sensing to leverage the state-of-the-art cellular technologies. The service-based network architecture, flexible and efficient waveform and advanced signal processing at the network node are the fundamental building blocks to enable the JCAS in cellular networks.

First, the network architecture could enable efficient coordination across the sensing nodes in the wide area network, which is a key feature compared with the classic radar sensing. A service-based architecture is the basis for the 5G core network, which could be further expanded into 6G for the RF sensing service.

In this scenario, it is expected that a network entity performs as a sensing server to coordinate the sensing nodes for sensing signal transmission and reception. For localization/tracking use cases, the multi-cell operation requires cross cell coordination through the sensing server. For example, the sensing server could enable efficient gNB grouping during the target tracking. The sensing server could also mitigate the inter-cell interference through time/frequency/code/spatial domain multiplexing across the cells. Moreover, the sensing server could also collect extensive measurements from both the UE and gNBs to facilitate the AI driven intelligent sensing service, such as target recognition and scene understanding.

Second, the standardized waveform and reference signals in cellular networks is another fundamental technique to facilitate the RF sensing. The waveform and reference signal should enable both the mono-static and bi-static/multi-static RF sensing with delay/Doppler/angle estimation. From a hardware implementation point of view, the reference signal transmission across slots should guarantee phase coherency for the Doppler estimation. The dynamic range of the waveform is also critical for long range sensing, especially for the small size targets, such as drones, so a low PAPR waveform is desirable.

Another desirable property for the waveform involves supporting efficient full duplex sensing. In the 5G life cycle, the OFDM based waveform could serve as the baseline for RF sensing, which could fully re-use the existing hardware. One enhancement could be using the DFT spread OFDM with Pi/2 BPSK for the RF sensing purpose (for example, introduce the low PAPR PRS in 5G advance). Looking ahead to 6G, further new waveforms could be considered to meet all the above desirable properties for RF sensing.

Finally, advanced signal processing needs to deal with two fundamental challenges in cellular based RF sensing: strong self-interference and rich clutter in the environment. The distribution of the self-interference and clutter in time, frequency and angle domain could motivate some advanced receiver algorithms to reject the interference with acceptable implementation complexity. Some example algorithms are Doppler shift-based interference rejection, sensitivity time control (attenuate the

nearby ground clutter which has an extremely large signal strength), moving target indication (moving target indication (MTI) uses signal processing to filter stationary and quasi-stationary clutter), space-time adaptive processing (adaptive weighting on the detected energy (signal, clutter, and/or noise), to discern the signal from clutter) and Constant False Alarm Rate (CFAR) detection (time-varying detection threshold that provides a constant false alarm rate to ensure that only the signals of interest are detected).

4. Intelligent Surfaces[28]

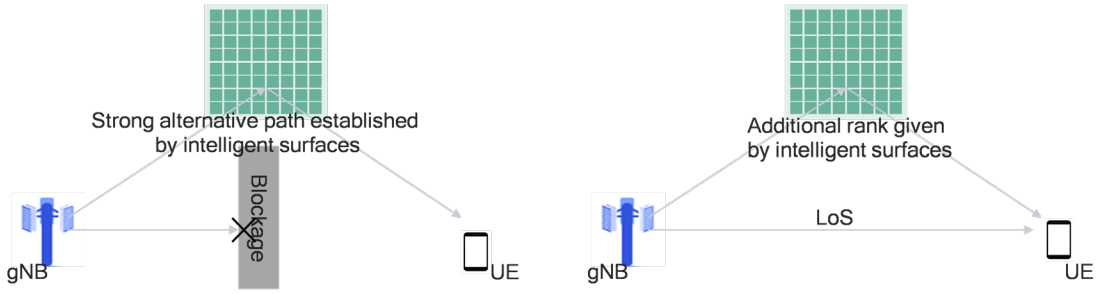
4.1 Motivation and use cases of intelligent surfaces

The intelligent surface has recently emerged as a promising new technology to achieve reconfigurable wireless channels/radio propagation environment. An intelligent surface is composed of many low-cost scattering elements called "unit-cells", which have properties that can be dynamically programmed to modify wireless signals into a desired way through reflection, refraction, focusing, absorption or any combination of these. By densely deploying intelligent surfaces in a wireless network and smartly coordinating their properties, the signal propagation between transmitters and receivers can be flexibly reconfigured to achieve desired realizations and/or distributions. Such deployment of intelligent surfaces could be applied in various scenarios such as outdoors, indoors, and out-to-in coverage extension including vehicle-mounted cases.

Figure 5 shows how intelligent surfaces can be used to improve coverage and capacity of wireless communication networks. By deploying intelligent surfaces in an appropriate location, line-of-sight (LoS) propagation paths between a transmitter and intelligent surface as well as between intelligent surface and a receiver can be established in such areas without strong direct coverage from the transmitter. In addition, if the intelligent surface can perform dynamic beam steering, then a larger number of UEs located weak coverage areas can be supported with improved link qualities.

In another deployment, intelligent surfaces can add extra signal paths toward a desired direction to improve the channel rank condition. When a strong LoS channel is established between the transmit antennas and the receive antennas, the number of eigen channels for parallel data transmission can be limited to one or two. By deploying intelligent surface, more eigen channels can be obtained for the wireless network to provide an increased spectral efficiency. Especially at higher frequencies, the channel is often dominated by a certain direction, where intelligent surfaces could significantly improve the rank property of desired UEs. Note that the above-mentioned coverage and capacity improvement via intelligent surface would be achieved between bast station to UE communications as well as UE to UE (sidelink or D2D) communications.

Figure 5. Intelligent surfaces for wireless communications: Enhancement of Coverage (left) and capacity (right) (Source: 5G Americas member company).



Other use cases of intelligent surfaces include generation of strong reflected paths or additional measurements in positioning, JACS, or wireless power transfer (WPT) systems.

4.2 Comparison intelligent surfaces with existing topology solutions

Traditional cellular network deployments are mainly based on fixed macro base stations (BS). In certain environments e.g., dense urban environments, there might be locations where a network performance from base stations may not be adequate, and it may cause a signal coverage problem. Densifying network sites by installing additional base stations on buildings or other infrastructure

sites or relocating cell sites could resolve these coverage problems. However, it may not always be an ideal solution and may bring challenges to the operators such as costs in site installation, power sourcing, backhaul availability, real estate permissions, regulations approval, and other challenges which may also require significant efforts and time. In view of these issues and limitations, it is imperative to develop disruptive new and innovative technologies to achieve a sustainable capacity growth of future wireless networks with low and affordable cost, complexity, and energy consumption.

Motivated by the above, integrated access and backhaul (IAB) and network-controlled repeater (NCR) have been developed in 3GPP as new types of network nodes to offer blanket coverage in cellular network deployments. IAB was introduced in Release 16 and enhanced in Release 17 to reduce dense network deployment costs by using in-band wireless backhauling to relay access traffic. That is, IAB serves as a complement to microwave P-to-P backhauling in dense urban and suburban deployments, while it comes at the expense of using IMT bands not only for access but also for backhaul traffic. However, since the basic function of IAB node is decode-and-forward relaying, both baseband and RF have to be implemented in the node which means the cost efficiency of IAB is coming from wireless backhauling without wire installation, not from the node implementation complexity.

Another type of network node is RF repeaters which amplify-and-forward any signal that they receive. RF repeaters have seen a wide range of deployments in 2G, 3G and 4G to supplement the coverage provided by regular full-stack cells. While RF repeaters present a cost-efficient means without baseband function of extending network coverage, it has its limitations that include not being able to take into account various factors that could improve performance, such as downlink/uplink configuration, adaptive spatial beamforming, ON-OFF status, and more. To address such limitations, 3GPP Release-18 has introduced NCR with the ability to receive and process side control information from the network which could allow an NCR to perform its "amplify-and-forward" operation in a more efficient manner, mitigating unnecessary noise amplification and providing better spatial directivity and simplified network integration.

Compared to IAB and NCR, the intelligent surface is expected to be a simpler relaying node which mainly relies on accurate beamforming capability without active amplification. That is, intelligent surfaces would be capable of signal reflection/refraction applying spatial phase compensation without complicated RF chains nor baseband implementation for relaying/forwarding. The lack of amplification of an intelligent surface would be compensated for by a large reflecting area which would typically be much larger than, for example, the antenna of an NCR. Due to such a distinctive relaying/forwarding mechanism, an intelligent surface would have different pros and cons from other solutions in a variety of ways, including implementation/installation complexity, energy consumption and coverage enhancement capability.

It should be noted that the purpose of an intelligent surface is not to compete with other topology solutions having different characteristics, but to rather offer another tool to a network deployment based on an optimal mix of different and complementary topology solutions.

4.3 Design goals and challenges for intelligent surfaces

The first design goal for intelligent surfaces is improving the propagation environment to enhance the coverage and spectrum efficiency of the system. An intelligent surface can achieve these by either increasing the path gain through lensing, or decreasing losses by enhancing surface transmittivity, or by introducing additional or alternate paths between the transmitter and the receiver. These may be achieved by the intelligent surface through accurately modifying the impinging wavefront by controlling the phase shifts introduced by each unit cell of the surface. Therefore, intelligent surfaces should be able to support the flexible phase configuration/reconfiguration to improve the link quality to the served receiver with a reasonable complexity. Such configuration/reconfiguration could be dynamic and/or semi-static, depending on the signal relayed by the intelligent surface. For example, broadcasting signals are forwarded with semi-static/periodic configuration, whereas unicasting signals could be relayed with dynamic configuration.

The second design goal for intelligent surfaces is using low-cost to improve the propagation environment. The cost of intelligent surface can be divided into implementation cost and deployment/maintenance cost. The implementation cost could be reduced by using advanced printing techniques to integrate low-cost electronic tunable components, such as varactors and pin diodes. To ease the deployment/maintenance cost, control and backhaul interface to setup and operate intelligent surfaces would need to be lightly designed as well as the overall power consumption by elements plus control unit should be limited (possibly being powered only by a renewable source).

4.4 Technology enablers for intelligent surfaces

The intelligent surface is composed of an arrangement of scattering elements with properties that can be dynamically controlled to change its electromagnetic behavior. That is, the response of intelligent surface can be controlled dynamically and/or semi-statically through control signaling. For such control, an intelligent surface could have two function entities, one is control unit to communicate with base stations or UEs to enable the control/assistance information exchange and control the elements, while the other is forwarding unit to perform the forwarding of RF signal. The behavior of the forwarding unit will be managed by a control unit according to the control/assistance information exchange from base stations or UEs.

Depending on which network node determines parameters of the scattering elements, the intelligent surface can be categorized into network-controlled, UE-controlled, and standalone types. For the network-controlled type with network node(s), such as a base station, can determine intelligent surface parameters based on UE sounding and/or CSI reporting followed by the communication with the control unit to update intelligent surface configurations. Such network-controlled types would be applicable to ordinary cellular uplink/downlink communications, where the scheduling function is typically located in the network side. Note that this is very similar to the network control of an NCR.

In some network scenarios, there may not be any central network nodes, like base stations, that could control the intelligent surface, but only devices/UEs. This could, for example, be the case in some distributed personal or local-access networks. In such scenarios, one of the UEs within the network may control intelligent surfaces to establish and maintain connection with other UE(s). Additionally, for sidelink (or D2D) communications out of base station coverage, the UE could be able to control intelligent surfaces to improve link quality between sending UE and receiving UE. In this case, mechanisms for discovery between UE and intelligent surface, reservation for UE to utilize intelligent surface, and intelligent surface configuration/reconfiguration would be needed.

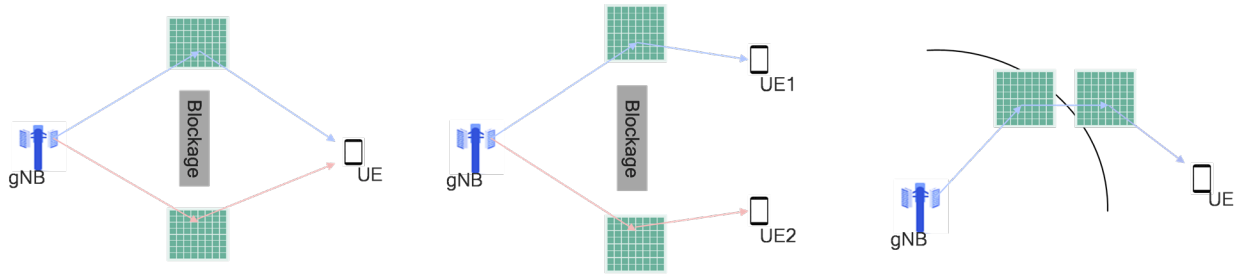
A standalone intelligent surface can determine its parameters to optimize the local system performance without control from other network nodes. That is, the angular position of nearby base stations and UEs are obtained by intelligent surface, and then the optimal configuration of intelligent surface parameters is locally computed and applied. As such, standalone intelligent surface would require advanced function implementation to detect surroundings and compute the optimized parameters.

To perform intelligent wavefront engineering, the intelligent surface will be composed on an array of unit-cells each of which can modify the amplitude and phase of the incident signal. That is, an essential aspect of intelligent surface is the reconfiguration of many elements to generate an accurate reflected or refracted wavefront with proper amplitude and phase values. Several reconfiguration schemes have been proposed to control intelligent surface. For example, the amplitude and phase value of each element is controlled to generate the optimal transmitted wavefront. A couple of near-optimal algorithms to control each element are already known to provide a promising performance gain.[29][30]

Intelligent surface reconfiguration could apply codebook-based beam control, where a set of amplitude and phase values, the so-called “codebook”, is designed for a given scenario and stored in the intelligent surface.[31] Based on beam sweeping of the intelligent surface, base station or UE can determine the best beam index and apply the corresponding beam for the forwarding.

The last technology enabler worth mentioning is coordination of multiple intelligent surfaces and/or multiple base stations. As shown in Figure 6, a proper coordination between multiple intelligent surfaces could realize higher rank transmission to a single UE, stable high-order multi-user MIMO, and multi-hop coverage extension. Additionally, coordination of multiple base stations to take advantage of adjacent intelligent surfaces could provide means to mitigate inter-cell interference, smartly applying intelligent surface beams and randomizing the interference.

Figure 6. Coordination of multiple intelligent surfaces (Source: 5G Americas member company).



(a) High rank for SU-MIMO (b) High-order MU-MIMO (c) Multi-hop coverage extension

Conclusion

5G has a significant road map of innovation ahead even as the mobile communications industry is at a critical juncture on the long road to 6G. Since 5G Americas issued its white paper "Mobile Communications Towards 2030" in late 2022, we are seeing the big picture of 6G research becoming clearer, with major regional and national research initiatives having launched. Progress is being made in research and initiatives, yet it is a bit too early to gauge their progress or identify any dominant technology trends.

At the same time, the main ITU and 3GPP 6G activities have yet to start, which will begin the transition from research to standards, industrialization, services and products.

In addition, 6G is being increasingly regarded by governments as a critical technology. The U.S. government has taken an active interest in 6G, including the NSC's "principles of 6G", and the U.S. government's "national standards strategy for critical and emerging technology". The CHIPS Act will also address 6G directly or indirectly in many of its parts.

In this paper, we investigated three promising technologies that could serve as important building blocks of 6G: Full Duplex, JCAS, and Intelligent Surfaces. We introduced each technology, then discuss its design goals and challenges, technology enablers and enhancement areas. We believe these technologies will help form the foundation of 6G wireless systems.

Appendix

Acronyms

AI: Artificial Intelligence

AoA: Angle of Arrival

AoD: Angle of Departure

ATIS: Alliance for Telecommunications Industry Solutions

BS: Base Stations

CFAR: Constant False Alarm Rate

CLI: Cross-link Interference

CPE: Customer Premises Equipment

CRB: Cramer-Rao Bound

CSI: Channel State Information

DDDSU: 3 downlink subframes, 1 special transition subframe, and 1 uplink subframe

DFT: Discrete Fourier Transform

DL: Down Link

ETRI: Electronics and Telecommunications Research Institute

GDOP: Geometric Dilution Of Precision

HD: Half Duplex

IAB: Integrated Access and Backhaul

ICT: Information and Communication Technologies

IIoT: Industrial Internet of Things

IMT: International Mobile Telecommunications

IoT: Internet of Things

JCAS: Joint Communications and Sensing

KAIST: Korean Advanced Institute of Science and Technology

KPI: Key Performance Indicators

LoS: Line-of-Sight

LTE: Long Term Evolution

MIC: Ministry of Internal Affairs and Communications

MIIT: Ministry of Industry and Information Technology

MIMO: Massive Input Massive Output

MOST: Ministry of Science and Technology

MoU: Memorandum of Understanding

MSE: Mean Squared Error

Appendix

Acronyms

MTI: Moving Target Indication

NCR: Network-Controlled Repeater

NextG: Next Generation

NICT: National Institute of Information and Communications Technology

NIST: National Institute of Standards and Technology

NR: New Radio

NSF: National Science Foundation

OFDM: Orthogonal Frequency-Division Multiplexing

PAPR: Peak-to-Average Power Ratio

PHY: Physical Layer

PRS: Positioning Reference Signals

RF: Radio Frequency

RFFE: Radio Frequency Front End

RINGS: Resilient & Intelligent NextG Systems

RTT: Round-Trip Time

SB: Sub-Band

SBFD: Sub-Band Full Duplex

SI: Self-Interference

SIC: Self-Interference Cancellation

SINR: Signal to Interference and Noise Ratio

SKT: South Korea Telecom

SNR: Signal to Noise Ratio

SNU: Seoul National University

TDD: Time Division Duplex

TDOA: Time Difference Of Arrival

ToA: Time-of-Arrival

UAV: Unmanned Aerial Vehicle

UE: User Equipment

UL: Up Link

WPT: Wireless Power Transfer

Acknowledgments

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Endnotes

1 https://www.5gamericas.org/mobile-communications-toward-2030/

2 https://www.nsf.gov/pubs/2021/nsf21581/nsf21581.htm

3 https://www.nsf.gov/news/special_reports/announcements/041822.jsp

4 https://www.thefastmode.com/technology-solutions/21559-vmware-mitacs-partner-to-pave-sustainable-path-for-6g

5 https://www.cnbc.com/2019/11/07/china-starts-6g-development-having-just-turned-on-its-5g-mobile-network.html

6 https://www.imt2030.org.cn/html/default/yingwen/Introduction/

7 https://b5g.jp/en/

8 https://www.soumu.go.jp/main_sosiki/joho_tsusin/eng/pressrelease/2020/11/27_04.html

9 https://www.nict.go.jp/en/press/2021/04/30-1.html

10 https://hexa-x.eu

11 https://hexa-x-ii.eu/

12 https://6g-anna.de/en/

13 https://www.6g-platform.com/

14 https://www.6gflagship.com/

15 https://www.lightreading.com/6g/we-want-to-be-first-to-6g-south-korea-government-plan-confirms/d/d-id/783334

16 https://www.itu.int/dms_pub/itu-r/oth/0a/06/R0A060000C80001PDFE.pdf

17 https://www.whitecase.com/insight-alert/president-biden-signs-chips-and-science-act-law

18 https://new.nsf.gov/tip/about-tip

19 https://www.nsf.gov/pubs/2023/nsf23090/nsf23090.jsp

20 https://ntia.gov/page/public-wireless-supply-chain-innovation-fund

21 https://www.defense.gov/News/Releases/Release/Article/3210295/dods-microelectronics-commons-takes-shape/

22 https://www.politico.com/f/?id=00000187-b4d1-d5cb-a7a7-b4d396280001

23 https://www.whitehouse.gov/wp-content/uploads/2023/05/US-Gov-National-Standards-Strategy-2023.pdf

24 https://ustr.gov/useuttc

25 https://www.keidanren.or.jp/en/policy/2023/028.html#p4

26 K. Kolodziej et al., "In-Band Full-Duplex Technology: Techniques and Systems Survey," IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, VOL. 67, NO. 7, JULY 2019.

27 3GPP TR 22.837: " Feasibility Study on Integrated Sensing and Communication".

28 Y. Liu et al, "Reconfigurable Intelligent surfaces: principles and opportunities," IEEE COMMUNICATIONS SURVEYS & TUTORIALS, VOL. 23, NO. 3, 3Q 2021.

29 B. Ning et al., "Beamforming Optimization for Intelligent Reflecting Surface Assisted MIMO: A Sum-Path-Gain Maximization Approach," IEEE Wireless Communications Letters, Vol. 9, No. 7, July 2020.

30 Y. Zhao et al., "Joint Transceiver and Passive Beamforming Optimization for RIS-Assisted MIMO Systems," International Conference on Wireless Communications and Signal Processing (WCSP), Oct. 2021.

31 X. Jia et al., "Environment-Aware Codebook for Reconfigurable Intelligent Surface-Aided MISO Communications," to be published in IEEE Wireless Communications Letters, 2023.