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CHARTING THE 6G COURSE: A COMPREHENSIVE SURVEY OF LEADING ASSOCIATIONS AND THEIR PIONEERING TRIALS

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Abstract— **The evolution of 5G networks into their mature state has generated interest in conceptualizing 6G networks. Leading powers such as the US, EU, and Asia have embarked on collaborative research and development initiatives with major telecom companies. Notably, Ericsson, Nokia, and Keysight have achieved significant speeds of 100 Gbps, while China has surpassed expectations with an impressive 200 Gbps. The shift to higher frequency bands has made traditional PCB antennas and feeder elements impractical due to heightened energy dissipation. In response, radio-on-glass (RoG) solutions have emerged as frontrunners for 6G line transmission. The pivotal role of Extreme MU-MIMO technology in achieving 6G communication necessitates a significant increase in the number of antenna elements, approximately five times more than those used in 5G networks. Nokia has introduced a compact RoD phased array prototype, complemented by an AI-AI radio interface capable of handling the algorithmic and computational complexity introduced by the scale-up. Advancements in IoT energy harvesting, illustrated by the 8development of zero-energy devices, and the creation of highly efficient lithionic neuromorphic circuits are being pioneered by Ericsson and MIT, paving the way for the realization of the "Internet of Everything." Simultaneously, Low-Orbit-Satellite (LEO) networks and Reconfigurable Intelligent Surfaces (RIS) are exhibiting promising outcomes, particularly in China, to enhance coverage and service quality.**

Keywords— **6G, 6Genesis Flagship, AI, Ericsson, Hexa-X, IMT, LEO, mmWaves, MU-MIMO, Next G Alliance, Nokia, orbital angular momentum, radio-on-glass, RIS, THz, zero-energy-devices**

I. INTRODUCTION

The standardization of 5G networks, officially announced with the release of 3GPP Release 15 in June 2018, marked the beginning of widespread global deployments of 5G networks. The development and improvement of the fifth-generation networks continues to this day, pushing the technology to its 5G-Advanced stage.

The constant market demands for different use cases (conventional and business models) enforces rampant development in the sphere of telecommunication networks. Given that, the newly presented and enhanced communication spheres - enhanced mobile broadband (eMBB), massive machine type communications (mMTC), and ultra-reliable and low latency communications (uRLLC) will not be enough to satisfy the technological requirements in period of seven years from now. This imposes the need for more advance technology, sequentially named as 6G. Many research and development (R&D) groups around the world, already started working on ideas which will premise the 6G technology. The work of the groups is closely related to certain associations and countries. The global race for 6G dominance is intensifying among key players in Europe, the USA, and Asia. In North America, the Alliance for Telecommunications Industry Solutions (ATIS) and the Next G Alliance (NGA) are leading initiatives with the support of major industry players. Europe, despite lagging with implementation of 5G technology, ongoing efforts are being made to bridge the gap through the funding of numerous organizations like Hexa, 6G-Flagship and many others, aiming to catch up with the advancements in 6G technology. Asia, particularly China, emerges as a formidable player in the 6G race, building on its dominance in 5G technology. Chinese companies and institutions are heavily investing in research and development, with the IMT (6G) Promotion Group leading the official launch of 6G initiatives.

Although the 6G is far from official standardization, the white papers issued by the relevant organizations are concentrating on similar evolvement directions, while placing the pillars on the same key technologies. The forecasted milestones, predict addition of two completely new communication spheres: Human Centric Services (HCS) and Multi-Purpose Services (MPS) [1], [2]. Peak downlink data rates exceeding 1Tbps, coupled with ultra-low delays of 0.1 msec, minimal jitter of 1 microsecond, and individual data rates of 100Gbps, represent a subset of the high expectations associated with the sixth generation of networks. These requirements place the technology in the sub-THz and THz range of the spectrum [3]. The higher spectrum region necessitates an increase in the number of network elements to successfully meet the forecasted specifications. With the added complexity, operating these systems solely through human intervention becomes nearly impossible, leading to the development of AI-operated or AI-supported interfaces. Traversing the path towards "Internet of Everything", the security domain is one of the key premises and the global coverage demands satellite-based communications. The primary objective of this survey is to spotlight leading 6G research and development organizations worldwide, showcasing their portfolio of groundbreaking achievements and trials in the realm of 6G.

The overall paper is organized as follows: Section II presents some of the most important achievements in 6G R&D on USA soil, mainly concentrating on the collaboration between NGA founding member - Nokia with Keysight and 3D Glass Solutions. The second Section is focused on presenting researches connected with the EU, with 6G Genesis Flagship and Ericsson as the main protagonists. Section III describes the R&D achievements promoted by Asian countries, focusing on the leading and breakthrough achievements of China and South Korea. The penultimate section gives a brief overview of the constraints and challenges brought up with the new generation networks. Finally, section V concludes this survey.

II. ALLIANCE FOR TELECOMMUNICATIONS INDUSTRY SOLUTIONS -- ATIS AND NEXT G ALLIANCE (NGA)

The Alliance for Telecommunication Industry Solutions (ATIS), accredited by the American National Standards Institute (ANSI), represents a North American Organizational Partner for the 3rd Generation Partnership Project (3GPP), a founding partner of the oneM2M global initiative, a member of the International Telecommunication Union (ITU) and a member of the Inter American Telecommunication Commission (CITEL). On 13th October, 2020 ATIS officially announced the launch of the Next G Alliance, presenting an industry initiative which aims at affirmation and advancement of North American mobile technology and 6G leadership in the following decade [4]. The Next G Alliance is set to embrace the full life-cycle of a technological market readiness, including research and development, manufacturing and standardization phases. The Alliance's Founding Members include many renowned names from the telecommunication world: A&T, Bell Canada, Ciena, Ericsson, Facebook, InterDigital, JMA Wireless, Microsoft, Nokia, Qualcomm Technologies Inc., Samsung, TELUS, Telnyx, T-Mobile, UScellular, Verizon, Apple and etc [4]. Next G Alliance is segmented among 6 working groups: Applications, Green G, National 6G Roadmap, Societal and Economic Needs, Spectrum, Technology [5].

A. Nokia and Keysight

The role of co-lead research collaborator is handed to Nokia Bell Labs [11], [12]. Nokia already partnered with multiple organizations, vendors, research teams and academic institutions in multiple technological spheres, pushing the 6G development further from day to day.

In order to achieve the goal, regarding the RAN interface, Nokia selected Keysight Technologies and 3D Glass Solutions as companions on the 6G road. To be more precise, Nokia Bell Labs has selected Keysight's sub-Terahertz (THz) testbed to verify the performance of 5G advanced and 6G transceiver (TRX) modules. Modules to be tested use the radio frequency integrated circuit (RFIC) technology, including power amplifiers, transceivers, and antennas on glass substrate, needed to support the extreme data throughput and reliable backhaul transmission requirements of 5G advance and 6G. For the antenna part and the on-glass technology, Nokia has selected 3D Glass Solutions. The whole solution can be described as D-band radio-on-glass with integrated transceiver and active phased array antenna. The basic setup for the 6G Sub-Terahertz R&D testbed is commercially available from Keysight [13]. It is a flexible and scalable solution supporting multiple frequency bands, frequency bandwidths, and waveforms. The solution covers D-band (110-170 GHz) and G-band (140-220 GHz) with a maximum bandwidth of 10GHz, and the H-band (220-330 GHz) with a bandwidth up to a 30 GHz. A rectangular horn antenna is used for transmitting the signal. The signal is then picked up by an identical horn antenna on the receive side. Antenna spacing is approximately 14 inches (35 centimeters). The testbed is very flexible, giving a plethora of possibilities for prototyping different candidate waveforms for 6G. Moreover, the testbed is multi-channel, making it suitable for MIMO research (Figure 1).

Fig. 1. 6G Sub-Terahertz R&D Testbed from Keysight [8]

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Why do we need a transition from good old PVC substrate to glass substrate? It is not a novelty that every technology tries to push the boundaries of the frequency ranges in use, in need for a wider available bandwidth and consequently possibility for increasing the throughput. The next generation aims at frequencies above 110 GHz, allowing it for speeds of 100 Gbps. At the same time, this will lead to shrinking of antenna size. All of these are great advantages for many deployment scenarios and use cases. However, there are many problems related to the usage of frequencies in the higher end of the spectrum, especially when designing the hardware elements. The classical PCB and antenna packaging does not perform well in regard to the new demands i.e. the loss is so high that no practical application is possible. More precisely, it is not enough to have a state-of-the-art RFIC, but also every part of the transmission line and the other components are of crucial importance. Given that, a new generation of low-loss materials is needed. The choice for this solution is the glass substrate. The radio-on-glass module, provides a loss of less than 1dB from the RFIC to the waveguide port of the antenna, for frequencies up to 150 -160 GHz. 3D Glass Solutions (3DGS) has developed and patented an ultra-low-loss empty Substrate Integrated Waveguide (eSIW) technology for high frequency Antenna-in-Package (AiP) and Radio-on-Glass (RoG) applications between 60 and 300 GHz [14]. The technology integrates all the necessary elements for a full RF Front-End into a single device, making it ideal for 6G applications. The collaboration between Nokia and 3DGS resulted in a 64-element 79GHz antenna for ADAS applications and a novel 64-element TxRx D-band (150GHz) Transceiver [15].

Nokia RFIC - Nokia has pushed the boundaries in the RFIC segment also. They have developed RFIC with 2 chipsets, operating between 115-155 GHz and 135-170 GHz, using SiGe BiCMOS technology, with record low-loss glass interposer technologies [16]. In the aforementioned frequency range, a transmitter P_{sat} up to 13 dBm and an average receiver NF of 8.5 dB is achieved. The module supports highly complex modulations for the D-band range. This is achievable due to the excellent linearity noise and gain performance. The results (Figure 2) demonstrated 512-QAM 9 Gbps (EVM = 2.24%) and 128-QAM 42 Gbps (EVM = 4.4%) at 145 GHz using Low-Band IC. The High-Band IC performed with 256-QAM 8 Gbps (EVM = 3.62%) at 170 GHz and 64-QAM 36 Gbps (EVM=6.94%) at 165 GHz. The measurements were performed at 7-10 dB of back-off power from P_{sat}. Nokia also demonstrated the performance Tx-to-Rx configuration, using two RoG modules, connected to each other with a 44 dB waveguide attenuator to mimic a 250-meter wireless link (assuming 40 dBi antennas on both ends). The results showed a performance of 64-QAM 36 Gbps (EVM = 7%) and 256-QAM 8 Gbps (EVM = 3.18%) at 135 GHz carrier frequency, which is state-of-the-art performance.

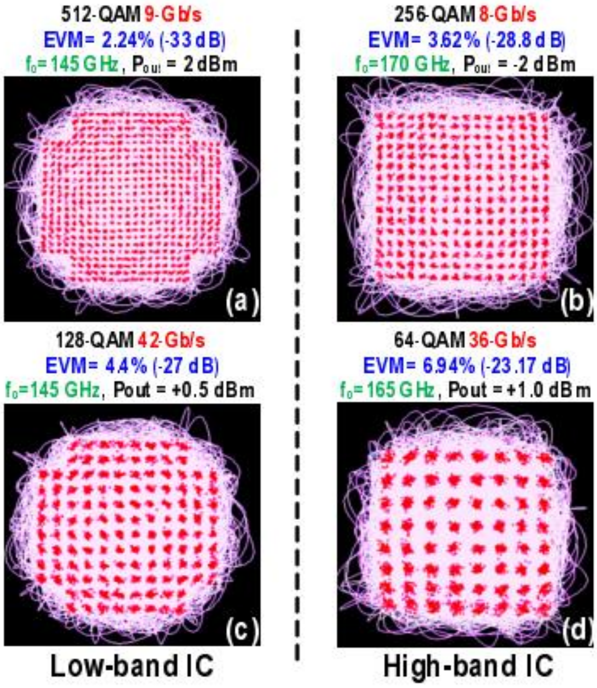

Fig. 2. Nokia RFIC - modulation and EVM measurements [11]

Extreme massive MIMO - In order to achieve the milestones and to meet the demands of the 6G, Nokia as many others, aims at extreme massive MU-MIMO [17]. Moreover, it is expected that the technological advances should occur at User Equipment side also, i.e. more advanced antennas and logic should be installed, providing UE beamforming. In the previous generation - 5G, massive MIMO using up to 200 antenna elements and up 64 TRXs was utilized. The next generation is expected to go up to 1024 antenna elements and 512 TRXs. Although, no practical testing is conducted on this magnitude, the system simulations showed that extreme mMIMO can provide 2.3 times more capacity [18]. In addition, it is estimated the UE beamforming can provide 2.2 times more efficiency. Combining these two, we get approximately 5 times higher spectral efficiency.

In the direction of beamforming, Nokia already presented a new phased array on RoG D-band module, using 8x16 slot antenna arrays (Figure 3). The results demonstrated an EIRP of 44dBm at 140 GHz, which is a world record result, given the level on integration and the glass architecture. As we go higher in the spectrum, within 7-20 GHz bandwidth, it is demanding that hybrid beamforming is applied. In hybrid beamforming, jointly beamforming between digital and analog architecture is performed. This leads to decreasing and optimizing the usage of components needed for realization of the extreme mMIMO, thus giving highest performance at lowest cost for a given deployment environment. As mentioned before, since large arrays are possible in the UE (in higher frequencies), the

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combined beamforming on network side and on UE side is expected drastically to increase the spectral efficiency.
Given all the above, there is a need for more advanced algorithms, both on Tx and Rx side, which sometimes can be computationally heavy if performed in conventional way. This naturally imposes the need for AI native interfaces, where different parameters will be produced and learned as a result of some deep neural network computation.

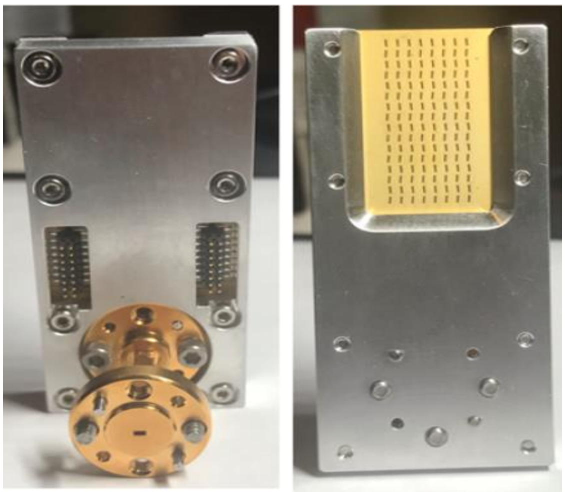

Fig. 3. Nokia RoG 8x16 slot phased array prototype [12]

AI-Native interface - As next-generation networks evolve, the demand for more efficient interfaces and operational methods intensifies. Manual intervention in network components becomes increasingly challenging due to heightened complexity. In response, the industry is shifting towards AI-Native Air Interface (AI-AI), a transformative departure from traditional communication system design and standardization. Nokia showcased a practical implementation of the AI-AI interface in a laboratory setting, demonstrating significant performance improvements [19]. Cyclic prefix-based OFDM with 72 subcarriers spaced 30 kHz apart is considered. Furthermore, assume transmission time intervals (TTIs) of 14 consecutive OFDM symbols which contain codewords of length 1024 bit at a code rate of R=2/3, generated by a 5G-compliant code. The non-ML baseline assumes 64-QAM, pilots transmitted on every other sub-carrier on the third and twelfth OFDM symbols, least-squares channel estimation, equalization based on the nearest pilot, exact demapping to log-likelihood ratios (LLRs) assuming a Gaussian post-equalized channel, as well as a standard belief propagation (BP) decoder.
Nokia's implementation involved three key phases, each addressing specific challenges in communication systems. In Phase 1, Nokia addressed channel aging and imperfect Channel State Information (CSI) by learning a specialized demapper for each Resource Element (RE). This approach led to a 0.5 dB gain over the baseline, enhancing the quality of Log-Likelihood Ratios (LLRs). However, this method did not fully mitigate the impact of channel aging.
To overcome this limitation, Phase 2 introduced a larger demapper that operated on the entire Transmission Time Interval (TTI) rather than symbol-by-symbol. Using a fully convolutional ResNet architecture with dilated separable convolutions, Nokia achieved remarkable performance, compensating for errors made by the channel estimator and equalizer. This phase resulted in a 2dB improvement over the baseline.
In the final phase (Phase 3), Nokia demonstrated the advantages of learning geometric shaping (GS) at the transmitter side. This involved jointly optimizing GS with the neural receiver from Phase 2. The learned constellation (GS) used on every RE showcased similar performance to Phase 2, but with the added advantage of not transmitting pilot symbols (Figure 4), resulting in a streamlined curve comparable to the one obtained in Phase 2. This innovative approach streamlines the process, illustrating the potential of AI to enhance communication systems.

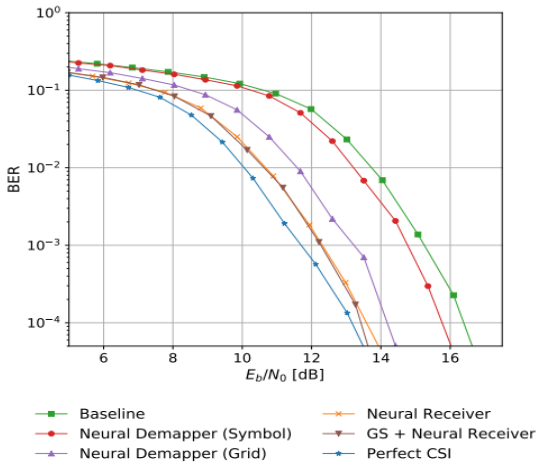

Fig. 4. BER performance of the AI-AI interface over the baseline, in reference to the perfect CSI [14]

III. EUROPEAN PROJECTS AND ORGANIZATIONS

Although in the middle of the 5G era and not many 5G SA deployments, Europe is still trying to catch on to the 6G train and to lay down the foundations for this critical future technology. The EU is funding 6G research through two leading projects: 6Genesis Flagship Program and Hexa-X – an initiative that falls under European Commission's Horizon 2020 financial instrument, and that is designed to promote EU leadership in various areas of technology.
Hexa-X is a project initiated by the EU in order to pave the way to the next generation of wireless networks (Hexa) by explorative research (X). The project started officially at the beginning of January 2021, with a planned duration of 2.5 years. Hexa-X vision is no different than the one described by every 6G white paper i.e., to sublimate the human, physical and digital worlds in one. The vision is driven by the ambition to

contribute to objectives of growth, global sustainability, trustworthiness and digital inclusion [15]. Hexa-X identifies the following critical technology enablers for 6G: sub-THz transceiver technologies, accurate stand-alone positioning and radio-based imaging, improved radio performance, artificial intelligence (AI)/machine learning (ML) driven radio access network (RAN), future network architectures and special purpose solutions include future ultra reliable low latency communication (URLLC) schemes [16]. Since it was mentioned that the planned lifespan of Hexa-X project was 2.5 years, we will introduce its successor - Hexa-X-II project. The latter is only a continuation of Hexa-X and lays over the fundamentals established by its predecessor. Hexa-X-II expands the list of partners from 25 to 44 organizations, aiming at creating pre-standardized platform and system view. This should form the basis for many inputs into future 6G standardization. One can find plenty of renowned organizations in the list: Nokia, Ericsson, Apple, Telefonica, Telenor, Sony, Siemens, Qualcomm, Orange and many others. %Given the many groundbreaking developments and researches, it is no strange that Nokia is chosen as an overall lead (coordinator) of the project. Following Nokia, is its well know competitor – Ericsson in the role of project's technical manager. The official start of this project is January 31st, 2023.

Beside projects natively funded by the EU, there are also separate projects and groups in different European countries, which are tightly connected with each other. Although there are many fractional organizations, they are all found by their country governments. It is worth mentioning 6G Access, Network of Networks, Automation & Simplification (6G-ANNA) [17], as representative from Germany, United Kingdom Research Institute (UKRI) [18] and 6G Flagship, part of the Finish government's national research program (2018-2026), standing as the world's pioneering 6G research initiative.

A. 6Genesis Flagship program

Moving on to European projects and organizations, the discussion shifts towards the 6Genesis Flagship program.

1) mmW and innovative beamforming - One of the main KPIs in the 6G domain is the drastically increased throughput and the issues that come with usage of significantly higher frequencies from the spectrum. 6G Flagship vision is to achieve extreme data rates, close to terabits per second, which is many times higher than the unofficial standard of ~100 Gbps. Besides the many issues that are to overcome, there is a substitutional decrease in antenna size. This gives the opportunity for realizing more antenna directivity and narrower beams for the same equivalent aperture size, compared to the lower frequencies from the previous generation. The demo uses beamforming technique for transmitting energy only to the directions that are useful. Given that it is possible to serve multiple users at the same time and at the same frequency and create multiple parallel links between the transmitter and receiver [19]. The set up uses a 28-GHz link in an antenna chamber, using 64 element antenna arrays on Tx side, implemented on 16 chain RF PCBs, lens antenna on Rx site and 8x100 MHz 64 QAM OFDM waveform. The radio transceivers are designed at the University of Oulu, which are key elements in the experiments conducted in the RF domain. Beamforming is mandatory in mmWave systems to get any signal through, and moreover is one of the key enablers in the 6G technology pillar. Additionally, the beamforming increases the energy efficiency of the system. The demo presents two beamforming techniques that can be utilized in both link ends. On transmit side the wavefront direction is changed by phase shifting the signals exited by the individual antenna elements. This results in RF beam that can be electrically steered to different directions. On receive side, as mentioned, lens antenna is used. The lens is similar like the one present in cameras. This technique of steering beams was not practically feasible in the previous generations because of the lower frequencies. Going up in the spectrum, 6G enables usage of lenses with descent and practical sizes.The demo demonstrated data rates up to 3.5 Gbps with potential capacity up to 6 Gbps.

In order to reduce the issue with high path loss in the radio channel and low output power at the transmitter, inherited from the high frequencies, it is required to use high gain antennas of 25 to 40 dBi, depending on application. In the IEEE 802.15.3d2017 standard, which defines the physical layer in the frequency range between 252.72 and 321.64 GHz, eight different channel bandwidths are defined, ranging from 2.16 to 69.12 GHz. Although this is not the official standard for the 6G technologies, it is often used in R&D practice as some kind of guide. The classical local oscillators in the mixer-type of transceiver architecture provides lot of spurious interference signals that might be attenuated by certain filter structures. In order to ensure high SNR, the classical approach is to use on-chip band filters at intermediate frequencies. Another approach is to use discrete filter on chip at sub-THz frequencies. 6G Flagship with other university groups made a step further by testing the effectiveness of meta-material structures located on the top of the antenna, which apply filtering on the radiated beam. To be more precise, 240 GHz operated meta-surface band pass filter consisting of split-ring resonator (SRR) matrix was simulated and measured as single and second order modes. The filter was integrated with hemispherical and Luneburg type of antenna lenses [20]. The SRR meta material was recommended component for 6G telecommunication application, characterizing measured values of 80 GHz bandwidth, low insertion loss (-0.75 dB) and good attenuation (-8 dB) characteristics close to the band pass region. Moreover, this filter can be used in cascade in order to obtain enhanced filtering characteristics.

2) Wood-based composite materials for ultralight lens antennas in 6G systems - The picture will not be complete if we don't introduce the novelty presented by this group, and that is lenses based on cellulose nanofiber (CNF) materials and wood nanofibers (WNF) [21]. In the sub-THz and THz spectrum, lightweight, sustainable materials with low electric permittivity (ε_r) and dielectric loss tan(δ) are crucial. RF lenses, used for increasing the capacity, gain and efficiency of the system, are often crafted from high resistivity silicon (ε_r ~11.9) or polymers ε_r ~2.3). These materials enable faster signal speeds and efficiency, yet their weight burdens the RF lens compared to integrated electronics, causing negative impact on the environment footprint. Structural porosity is a highly utilized technique for relative permittivity reduction, resulting in ε_r ~ 1.05 in polymer materials. The Hollow Glass Microspheres (HGMS) are cost-efficient to reduce the er and losses of circuit boards, thick film devices or EM-shielding. In order to utilize the HGMS as a porosity-adding material, while eliminating the risk of microspheres crushing during the process, the group suggested cellulose nanofiber (CNF) suspension. The last can be used as a bio-binder, mixing with the filler materials without using additional pressure or strong shearing force. Combination of CNF-HGMS forms a lightweight composite material, which is non-plastic, sustainable and environmentally friendly. Moreover, there are plenty of ways for producing CNF. The research group chose three types of CNFs: obtained from deep eutectic solvent treatment (DES CNF), TEMOPO oxidized CNF (TO-CNF) and wood nanofiber (WNF). The later were compared to Silicon and Teflon materials, which lead to conclusion that indeed, the new generation of materials are compliant with the 6G requirements.

B. Ericsson

Shifting the focus to Ericsson, a well-stablished name in the telecommunication community, both in the business and R&D fields. It is one of the leading providers of Information and Communication Technology (ICT) to service providers. Its history of 145 years speaks more than enough about the company and the influence in the telecommunication sector.

Although Ericsson is inseparable part of the Next G Alliance, the biggest deployments and research institutes are concentrated in Europe. Given that, Ericsson's achievements in 6G will be described in this section.

1) Ericsson's Terahertz Transmission - At the 2023 Mobile World Congress (MWC) Ericsson presented several 6G demos, related with different topics [22]. Expectedly, there was a full live THz transmission demo, representing the basis of 6G technology. The transmission occurred in the 100 GHz transmission frequency band, utilizing a 4GHz bandwidth and OFDM modulation with QAM-256 symbols. A data rate of 102.5 Gbps was demonstrated, which is 200 times faster than 5G median download speed in South Korea. However, not many details about the setup were published to this day. Accompanying this presentation, a sensing demo was demonstrated. The demo presented a system which utilizes the Ericsson's THz solution and is capable of identifying when a certain user is out of reach. After the user exits the zone of coverage, the radio unit pauses video streaming. This leads to more efficient use of radio resources.

2) Zero-Energy devices and lithionic chips - Ericsson Research and MIT announced a collaboration at the beginning of July 2021. The aim of this collaboration lays its ground on two major projects, designing the state-of-the-art hardware to power next-generation 5G and 6G networks. Lithionic chips – Lithium is a well know element in state-of-the-art batteries, like the one that can be found in electric cars. Recently, the research group in MIT, lead by professor Jennifer Rupp and Martin Bazant, showed that some of the battery electrodes made from lithium are also ideal for other applications, including computing [23]. Lithium oxide materials could be a key component to memristors. Memristors require much less power than conventional transistors because they utilize two features – data storage (memory) and data processing, all packed in one unit. This saves the process of transferring data between different units/circuits, this making them highly more efficient than the existing ones. What is interesting is that they are capable of executing neuromorphic computing, which involves a set of chips that mimic the structure of the human brain. The group is working on prediction of best lithium compositions for lithionic computing applications, and their implementation in neuromorphic circuits. Ericsson researchers will participate in the evaluation of algorithms and hardware architectures comprising lithionic devices.

If we paraphrase the 6G mission, it is easy to conclude that in the future, the number of devices connected to the internet will steeply increase. Some analysis predicts numbers in the range of hundreds of billions or even trillions of devices. This imposes the question of energy harvesting in order to make these networks feasible and sustainable. The goal is to make devices that will be as autonomous as possible. Given that, Ericsson and MIT introduced the term zero-power devices [24]. The name describes a feature where no additional wires or batteries will be needed in order for the device to function as designed. The first demo demonstrating zero-energy devices was presented on MWC 2023 by Ericsson. The setup included chips that can be attached to clothing and fabric, which are powered and harvest energy from radio signals. Additionally, it is planned to reinforce and optimize the operation of zero-energy devices by introducing ML algorithms which will improve the transmission protocols and the radio interface.

IV. 6G ASIA

In the dynamic landscape of 6G development, Asia emerges as a formidable player, spearheading ground breaking advancements in satellite-based communications, millimeter waves (mmWaves), and intelligent surface technologies.

As representative form the Far East, China is maybe the most serious player in the 6G race. Driven by their dominance with the 5G, both on a technological and business level, they are investing every resource - financial, corporate and academic, in the R&D and standardization of the 6G. The dependency of Chinese vendors and technology plays a big role on the world's scene and to this date there is no suitable substitute. Furthermore, according to the last available stats, 40.3% of all 6G patent filings are from Chinese applicants. They were followed at 35.2 percent by the U.S., Japan at 9.9 percent, Europe at 8.9 percent and South Korea at 4.2 percent. However, as the time progress, more and more organizations, academic institutions and governments around the world, are entering the 6G race, boosting the potential and making it hard to predict the final outcome.

On Nov.3 2019, China's science and technological ministry has formed an expert team to start working on sixth-generation wireless telecom technology research and development, marking the official launch of 6G. Although this is the first official initiative, it is speculated that the research in the domain started somewhere in 2018. The group consists of more than 70 experts from universities, research institutes and tech companies who are mainly tasked with drafting the 6G research blueprint and conducting technical demonstrations, as well as defining guidelines and making major decisions. The official name of the group is IMT (6G) Promotion Group of China. Many leading companies are part of the group: China Mobile, China Academy of Information and Communications Technology (CAICT), China Unicom, HUAWEI, ZTE, Ericsson, Nokia and many others.

If we take a look in the white paper issued by IMT 2030 [25], we will see many similarities with the white papers and targets presented in the sections above. However, it's crucial not to overlook the achievements of other Asian countries. Analyzing the patent distribution reveals that Asia surpasses the USA and Europe. South Korea, for instance, invested $324.5 million in its 6G development program led by the Ministry of Science and ICT (MSIT). They are actively participating in the 6G satellite communication technology race with initiatives like CubeSats, Project 425, the Korean Positioning System (KPS), and LEO satellite communication. Simultaneously, LG is pushing the boundaries with successful wireless transmission and reception of 6G terahertz (THz) data over 500 meters, the longest distance recorded in any 6G test conducted in an outdoor, urban area to date.

Japan partnered with the USA to develop 6G standards, aiming to prevent Chinese dominance. NTT Docomo, a Japanese telco, initiated experimental trials in 6G in collaboration with Nokia, Fujitsu, NEC, Ericsson, and Keysight Technologies.

C. First 6G Satellite and Low-Orbit-Satellite networks

China was pushing the race for next generation networks even before it became mainstream in the R&D community. The satellite-based communications are believed to be a crucial part of the 5G-Advanced and 6G eras [26]. This can be backed up with the official start of "non-terrestrial network" (NTN) researches under the wing of 3GPP. Non-terrestrial communications are crucial in supporting extreme and "3D" coverage of the Earth. Additionally, the NTN communications can provide high-precision positioning and navigation. On Nov.6 2020 China successfully launched a Long March 6 rocket, with intention of placing 13 satellites into orbit. One of the satellites was described as "the world's first 6G satellite". The official name is Tianyan-5. The Tianyan-5 is a remote-sensing satellite that has been jointly developed by the University of Electronic Science and Technology of China, Chengdu Guoxing Aerospace Technology, and Beijing Weina Xingkong Technology. The satellite is equipped with terahertz generating modules, and its main purpose beside the 6G use-case is to test if the improved signal strength and latency speed can help to monitor climate change developments in real-time.

Another key player in this segment is the Chinese space startup - GalaxySpace. The went a step further and launched China's first low-Earth orbit (LEO) broadband satellite constellation (March,2022). The constellation consists of six 5G capable satellites, with one additional satellite launched back in January 2020. Although, at first glance this seems like a race with the existing SpaceX's Starlink service, it also represents a network for testing future-proof 5G-Advanced and 6G use cases. In June, 2023, the company performed the first successfully interconnection between a space-based system and ship on the high seas, using the aforementioned constellation. The latest, in July 2023, the company launched a state-of-the-art communicating satellite, named Lingxi-03. The satellite is equipped with a millimeter-wave multi-beam digital payload with a capacity of tens of gigabits per second. It will be used to verify technologies, including the next generation of low-Earth orbit broadband satellite communication. According to GalaxySpace, in the approaching 6G era, satellite internet will support the ubiquitous network demand of the Internet of Everything, solving connectivity issues in remote places, oceans and aviation.

D. Vortex mmWaves

China's research team, lead by Zhang Chao, claimed that they have achieved a data streaming record, using vortex millimetre waves for transmission. This is also known as orbital angular momentum (OAM) multiplexing technology [27]. The main feature of these techniques is the addition of another dimension in contrast to the conventional plane-waves. This leads to vortex-shaped waves. However, there is one main issue - the size of the spinning waves grows larger with distance, making high-speed data transmission difficult. The research team managed to construct a high-performance receiving device that could take up and decode a large quantity of data in a split second, as well as a novel transmitter that generated a more concentrated vortex beam and made the waves spin in three distinct modes to convey more information. The experimental wireless setup was deployed in the Beijing Winter Olympics and simultaneously streamed more than 10,000 HD live feeds seamlessly. The final results presented transmission of 1 terabyte of data over 1km in one second [28].

E. Above 100Gbps

Recently, multiple vendors announced that they have reached the 100Gbps transmission rate milestone (Ericsson, Keysight) using sub-THz or THz connection. The researches at Purple Mountain Laboratories (government fund lab in China), stated that they achieved a wireless transmission rate of 206.25 Gbps, placing a world's record. According to the released statement, they were able to achieve 100-200 Gbps real-time THz using a 360-430 GHz high-end wireless communication system, developed as a in-house solution [29].

F. Reconfigurable Intelligent metaSurface (RIS)

In September, 2022, the major international provider of telecommunications equipment and solutions - ZTE, in collaboration with China Mobile Research Institute, has completed the verification phase of the industry's first prototype, which integrates 5G base station and dynamic Reconfigurable Intelligent metaSurface (RIS) collaborative beamforming technology [30]. This represents a big leap from the previous fixed-point RIS assisted technology, which aimed at improving blind spots and weak-signal areas. The novelty proposed by the joint project, involves implementation of dynamic collaboration between the 5G BS and dynamic RIS. The main logic behind this technology is the digital dynamic configuration of the intelligent surface. Through beam ID and other configuration parameters, the 5G BS instructs the RIS to dynamically select and switch beams. This solution applies the key 6G technology of RIS into 5G networks. Moreover, given the fact the 6G is not strictly defined as technology, this is the only feasible test-bed scenario in industrial environment. The lab results demonstrated increase of the maximum RSRP by 27 dB and the user rate by 5.4 time, in regards to fixed-point RIS.

In August, 2023, China Mobile and ZTE successfully completed application verification of 5G-A/6G RIS, at the cycling stadium for the 19th Asian Games in Hangzhou. The outdoor tests just confirmed the previously obtained laboratory results.

G. Breakthrough technology for THz Waves amplification

Researchers at UNIST, South Korea, led by Professor Hyong-Ryeol Park, have developed a groundbreaking technology capable of amplifying terahertz (THz) electromagnetic waves by over 30,000 times, a significant advancement for 6G communication frequencies [31]. Using an AI-based inverse design method, the team optimized THz nano-resonators in less than 40 hours on personal computers, achieving an electric field enhancement of 32,000 at 0.2 THz, a 300% improvement over previous results. The novel approach combines THz nano-resonators with AI learning based on a physical theoretical model, offering a practical alternative to time-consuming numerical simulations for THz nanodevice design.

V. 6G CHALLENGES

In the sections above, a subset of pioneering trials and methods linked to the development of 6G networks were introduced. Although the results are astonishing, most of them were conducted in lab or controlled environments. The forecasted potential of the new generation network is huge, but the main question is which subsets of use cases will be practically available. Despite the main technological aim being to provide extreme rates, merge digital and physical worlds, enable the Internet of Everything (IoE), extreme densification, and global coverage, we must be aware of technological and business limitations on the implementation road.

It can be concluded that the objective is to use the sub-THz and THz part of the spectrum. This may be a novelty in the classical telecommunication sector, but, in fact, the aforementioned frequencies were already studied in radio astronomy and space science. However, the main difference is that when talking about terrestrial communication, which includes the air medium with obstacles, the THz waves experience immense propagation loss. This imposes the challenge of finding more degrees of freedom and constructing ultra-sharp beamforming with high angular resolution. The role of short-range communication will drastically increase, leading inevitably to more base stations. Given the frequency range, it will be almost impossible to penetrate through walls while maintaining the forecasted specifications that define 6G technology.

This constraint will force the implementation of indoor base stations, opening new value chains and business models. The Radio Spectrum Policy Group (RSPG) in the European Commission is already pushing for a new local frequency licensing model. Additionally, as stated in the above sections, the existing RFIC and PVC substrates are not able to cope with the demands of the THz range. Last but not least, technological solutions must be in line with regulations for human health exposure [32].

The paradigm of 6G wireless network requires global coverage and cooperation between terrestrial and satellite networks. Constellations of LEO, VLEO, and GEO satellites should be launched to provide omniconnectivity. The expenses of the implementation will open the market to new business chains, where most probably the Mobile Network Operators (MNOs) will not be the only ones providing the services.

Going towards the Internet of Everything, multiple prerequisites stand in the way. Firstly, it would be challenging to successfully operate heterogeneous networks in a cooperative way. New efficient algorithms need to be developed to efficiently serve the multitude of devices while ensuring appropriate Quality of Service (QoS). Multi-tier networks need to be carefully designed, satisfying two opposing sides - interoperability and segregation. Additionally, the immense densification and increase of connected devices will impose a serious load on the backhaul network. New ways of efficient and predictive caching should be employed at the edge network [33].

Native AI interfaces are ubiquitous when talking about 6G. The overall complexity is too big to be handled only by human personnel. Many organizations see potential in developing self-healing networks that will help with predicting and diagnosing issues in the network. While there have been attempts to develop AI interfaces, the lingering question pertains to the duration required for training these interfaces and the amount of data necessary for their effective functioning. These models must be designed with great caution to avoid leading to unwanted load and congestion in the networks.

VI. CONCLUSION

This survey outlines a very small portion of the 6G R&D challenges, aims and achievements, with general focus on pioneering and record-breaking researches. Following the technological evolvement phases, the expectations are that overall vision and technological framework have reached the finishing stages of establishment. The numerous white papers are solid proof of the convergence of the idea and technological road behind 6G. However, no official standardization and regulation is expected before 2025, with aim for commercial deployments around 2030. It is almost certain that the new generation of networks will utilize the sub-THz and THz range of the spectrum, allowing for substantial increase of the data rates and improvement of the delay and jitter parameters. So far the results demonstrated data rates about 200 times higher than the average 5G rates. These achievements and goals impose a series of changes in the hardware and software part of the devices. New substrates and materials, like glass and cellulose, are prerequisites for efficient transmission of signals and cost-effective implementation. The mass penetration of devices will force AI operated interfaces and coverage assistance of LOS networks.

Acknowledging the substantial leap from the current network technological standpoint to the envisioned 6G networks, it's essential to recognize that the associated constraints and requirements may pose significant challenges to successful realization. However, this journey serves as a notable illustration of the technological road map and appetites that are likely to remain pertinent for future network generations, highlighting the persistent drive towards advancements in network technologies

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