Back to Single-carrier for beyond-5G communications above 90 GHz

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Deliverable D1.2

Final regulation status, Scenarios and Requirements updates

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Executive summary

Enhanced or new wireless broadband applications will be enabled by the exploitation of sub-THz frequencies between 90 GHz and 300 GHz, arising with next 6G mobile network generation. Three main use case families are targeted: high-capacity backhaul; enhanced short-range hotspot; and device-to device communications.

This deliverable D1.2 gives an updated definition of use cases and requirements that were first published in deliverable D1.0 in November 2018, and then were considered in BRAVE studies. Also, a two-fold paradigm is exposed for the physical sub-THz layer that answers those use cases either with ultra-high data rates or a broadband low-complexity (and low-energy) system or in-between compromises.

The status on international and French sub-THz regulation remains roughly unchanged since the publication of our previous deliverable D1.1 in December 2019.

Finally, investigations on future 6G technologies, applications, requirements, and impacts are gaining more and more intensity since 2018. This document gives a brief overview on few relevant publications (often in the form of white papers) sharing the vision of major equipment vendors, industry alliances, or researchers, on 6G communications and sub-THz/THz spectrum exploitation.

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List of Acronyms

3GPP	3rd Generation Partnership Project
5G	5th Generation
6G	6th Generation
ADC	Analog to Digital Converter
B5G	Beyond 5G
CEPT	Conférence Européenne des administration des Postes et Télécommunications
CMOS	Complementary Metal Oxide Semi-conductor
DAC	Digital to Analog Converter
GSA	Global mobile Suppliers Association
ICT	Information and Communication Technology
IQ	In-phase In-quadrature
IEEE	Institute of Electrical and Electronics Engineers
LAN	Local Area Network
MAC	Medium Access Control
MTC	Machine Type Communications
MIMO	Multiple Inputs Multiple Outputs
RF	Radio Frequency
RIS	Reconfigurable Intelligent Surface
RR	Radio Regulation
SDG	Sustainable Development Goals
SC	Single Carrier
UN	United Nations
WLAN	Wide Local Area Network

1 Introduction

The technological research as well as the elaboration of a social, economic and technical vision on the next mobile network generation has experienced a very strong acceleration since our first publication on BRAVE scenarios and requirements in November 2018 [1], which have to be updated here.

A recent report by IDTechEx [2] estimates that the 6G technology will become the dominant mobile network infrastructure around 2037 (after an overlap period with 5G), and will generate a $1 trillion opportunity for telecommunication actors. In addition to the enhanced mobile broadband performance (100 Gbps to 1 Tbps) and ultra-low latency, 6G will offer sensing, positioning and distributed AI (artificial intelligence) unprecedented capabilities. A deep implication in our future societies, individual lives, mobility, industrial activities, etc, is expected, therefore ICT becomes an even more critical sector. Technological leadership or sovereignty have to be guaranteed, which encourages the governments and companies to heavily invest, for instance in ambitious beyond-5G research programs: the Finnish 6G flagship initiative launched in 2018; the North-American NEXT-G alliance created in October 2020; the “digital China” objective with 6G as a top priority in the new 5-years plan announced in March 2021; or the H2020 flagship HEXA-X research project started in January 2021.

The research effort is gradually migrating from 5G to beyond-5G considerations (however the frontier is not very strict). The first edition of the 6G wireless summit occurred in March 2019, under the impulsion of the Finish 6G flagship. Then other similar initiatives have been launched in 2020 and 2021. All major wireless communication conferences do now propose keynotes or workshops devoted to future 6G systems, and covers the main enabling technologies e.g. RIS (Reconfigurable Intelligent Surfaces), distributed MIMO or THz frequencies.

Besides, the Sustainable Development Goals (SDN) defined by the United Nations (UN) for horizon 2030, in particular when dealing with digital inclusion and climate change, have been integrated as necessary drivers to decide the targeted societal and environmental impacts and assess the proposed evolutions and.

Section 2 of the present document does report on the main trends that have emerged regarding the beyond-5G use cases, and the consequential challenges.

Section 3 gives an update on the regulation status, first established in our deliverable D1.1 [3].

And final BRAVE vision on the 6G sub-THz technology is described in section 4.

2 Emerging 6G vision and 6G-enabled use cases

Many equipment vendors, operators and industrial organizations, as well as some standardization or pre-standardization groups, have now given their vision on the future 6G generation: main use cases; societal, economic, and environmental impacts; and promising technologies. This section does not give an exhaustive view on those many propositions, but some highlights and valuable links.

A white paper by Samsung Research in 2019 [4] draws one of the first 6G visions that has been publicly shared. The 6G generation is expected to "provide ultimate experience for all through hyper-connectivity involving humans and everything". Machines will actually become the dominant mobile users; and 6G could have to connect hundreds of billions of them. New applications such as true immersivity, mobile holograms and accurate digital twins might emerge. Besides, the achievement of UN SDG's will take benefit of the 6G capability to give fast and ubiquitous access to information and services; and regional discrimination could be reduced.

BRAVE has published its own vision on broadband 6G applications using the sub-THz spectrum in September 2019 [5]. We distinguished between three main use case categories that could take great benefit of hundred's of Gbps: ultra-high capacity backhaul; enhanced hotspot; and ultra-fast shot-range connectivity.

The 6G summit brought together a group of international researchers to write a first white paper published in September 2019 [6], but also, an ambitious series of 12 white papers released between mid-2020 and mid-2021 that cover a wide range of topics incl. overall vision, use case requirements, spectrum opportunities, technology concerns from the physical layer up to the applications.

KPI	5G	6G
Peak data rate	20 Gb/s	1 Tb/s
Experienced data rate	0.1 Gb/s	1 Gb/s
Peak spectral efficiency	30 b/s/Hz	60 b/s/Hz
Experienced spectral efficiency	0.3 b/s/Hz	3 b/s/Hz
Maximum bandwidth	1 GHz	100 GHz
Area traffic capacity	10 Mb/s/m²	1 Gb/s/m²
Connection density	10^6 devices/km²	10^7 devices/km²
Energy efficiency	not specified	1 Tb/J
Latency	1 ms	100 µs
Reliability	$1\text{-}10^{-5}$	$1\text{-}10^{-9}$
Jitter	not specified	1 µs
Mobility	500 km/h	1000 km/h

Figure 1: Key performance requirements (from 6GFlagship [7]).

The white paper on 6G broadband connectivity [7] considers peak data rates up to 1 Tbps, and broadband connectivity for speeds up to 1000 km/h. The point-to-point higher data rates will be offered by THz frequencies complemented by visible light communications. "At the protocol/algorithmic level, the enablers include improved coding, modulation, and waveforms to achieve lower latencies, higher reliability, and reduced complexity", which is pretty well aligned with the problematics we have addressed in BRAVE project. In addition to THz communications, the white paper [7] expects the ultra massive MIMO, holographic radio, cell free networks, and IRS will permit to reach the targeted broadband performance.

The digitalization of many vertical sectors like industry 4.0, intelligent transport, smart cities will be engaged with 5G but need for further optimized Machine Type Communication (MTC) services [8], including massive connectivity, ultra low latency, ultra reliability (as for autonomous driving), low energy systems, together with mobile broadband (e.g. for data-hungry devices involved in immersive or digital twin applications).

White paper [9] stresses the crucial role of new allocated frequencies in particular in the THz spectrum in order to answer the data rates required for backhaul, augmented/virtual reality, kiosk and home broadband. It is also pointed the high frequencies will contribute to joint high-precision sensing and communication services, but also to imaging, security and health applications (due to their detection capabilities). IEEE standardization work is already on its way at THz frequencies: "standardization especially in Wireless Local Area Networks (WLAN i.e. 802.11 family) and high-rate Wireless Speciality Net-works (WSN i.e. 802.15.3 family) is moving gradually from tens of Gbps beyond 100 Gbps". Finally, it is worth noting the optical communications technologies are now considered for application at lowest frequencies i.e. in the wireless domain.

Industry alliances are also sharing their view and requirements, for instance NGMN (Next Generation Mobile Networks Alliance) led by world-leading network operators and gathering vendors and other stakeholders, or the 5GIA (5G Infrastructure Association) composed of a large range industry and research institute partners to promote and support European leadership.

In [10], NGMN states "the role of communication networks expands in every aspects of the society. Therefore, factors such as the following will be central in considering future technologies: cyber security, resilience (to climatic events, cyberattacks, equipment failures, software bugs, human errors, etc.), end-to-end environment impact of our ICT industry, energy efficiency and digital inclusion." Sustainability and the carbon neutrality must be a key focus, and have to be considered in the fundamental design of new technologies. NGMN suggests an holistic approach is required, where the impact of the global ecosystem (incl. user terminals, service footprint, reusability, repairability, recycling, …) is taken into account, relying on metering, monitoring, and appropriate deployment strategies.

Besides, 5G IA stresses Europe must be able to deliver secure, trusted and independent 6G network solutions and services, as this new technology will deeply modify the way we live and work [11]. For instance, the capability to dissociate the location of a human operators and the machinery will have a strong impact on the territories. 5G IA also considers THz as a key enabler, but it will faces obstacles "in efficient implementation due to the physical constraints of modern semiconductor and packaging technologies. New materials (like graphene) may play a role when they become mature for mass production. Before that, the solutions will rely on novel RF architectures, continuous development on antennas, packaging and semiconductor processes in a careful balance between performance and cost. Other challenges in this area include, e.g. new THz channel models, new waveform and modulation schemes, new experimental platforms and testbeds, novel MAC protocols, modelling and mitigation of non-linearities and phase noise, ADCs/DACs for tens of Giga samples/sec with reasonable power consumption, beamforming schemes for meeting 6G requirements in terms of coverage, mobility and robustness; efficient realizations of MIMO antenna arrays and transmit/receive chains, regulation and standardization of THz bands, etc.”

Ericsson [12] shares its key expectations, as shown in Figure 2, to make the next generation of mobile networks a trusted, sustainable, efficient and useful technology, that becomes an intrinsic part of the future society. Digital twins, automation, health applications, and immersivity are major uses cases, while digital inclusivity is to be achieved at a global scale.

Figure 2: Increasing expectations, as expressed by Ericsson [ERI].

In [13], Nokia Bell Labs explain how massive broadband low-latency communications will permit the constitution of a real-time digital twin, and creation of new mix of physical and virtual worlds. Besides, its is expected “new man–machine interfaces […] will make it substantially more convenient for us to consume and control information.” See Figure 3. Finally, Nokia Bell Labs give of a description of the mobile communication use cases (Figure 4), starting from those already or partly enabled by 5G, then moving to a set of new pure 6G applications. Those use cases are converted into a series of requirements, partly aligned with those given above in Figure 1, but also including interface and positioning considerations.

Figure 3: New 6G expected devices, as illustrated by Nokia Bell Labs [Nokia].

Use case (capability)	5G	6G
Augmented Reality for Industry	Low resolution / high level tasks	High resolution, multi-sensory / detailed tasks, co-design
Telepresence (capacity)	High video quality, limited scale	Mixed reality / Holographic
Security surveillance, defect detection (positioning & sensing)	External sensing, limied automation	Integrated radio sensing, fully automated
Distributed computing, Automation (time synchronization)	Microsecond-level tasks	Higher precision nanosecond-level tasks
Dynamic digital twins and virtual worlds (real-time, multi-sensory mapping and rendering)	No	Yes
Wireless in Data Center (peak rate and capacity)	No	Yes
Zero Energy Devices (back scatter communications)	No	Yes
Swarms of robots or drones	Maybe	Yes
Bio sensors and AI	Limited	Yes

Figure 4: :6G use case [13].

We finish this overview with some standardization. The IEEE 802.15.3d was officially approved in 2017 [14] for broadband wireless communications in the sub-THz spectrum i.e. from 252 GHz to 321 GHz with 8 possible channel bandwidths between 2.16 GHz to 69 GHz. It offers 100 Gbps data rates or above for point-to-point links in ranges between a few centimeters to a few hundreds of meters. Target applications are wireless backhaul e.g. for ultra-dense small-cell deployments, connectivity inside data centers, kiosk download, and intra-device wireless communications. The development of equipement supporting the IEEE 802.15.3d standard is at a prototyping stage today.

3 Sub-THz regulation

There has been no major decision regarding national or international sub-THz regulation since our previous regulation status in December 2019 [3].

Attribution of sub-THz frequency bands to fixed and mobile services by the international radio regulation (RR) is unchanged, with frequencies protected by footnote RR 5.340 for scientific services.

The European regulator CEPT has no action today regarding frequencies above 90 GHz, however mobile telecom industries (e.g. GSA or 3GPP) have mentioned some interest. ECC recommendations on fixed services published in 2018 [3] still constitute the up-to-date European contribution on sub-THz spectrum regulation.

As well, the French regulator ANFR has not been requested yet for sub-THz investigations.

4 Updated vision for BRAVE physical layer

BRAVE vision on beyond-5G sub-THz mobile communication has been refined since preliminary publications in 2018 and 2019 [1] [15] [16]. In particular, we have proposed a dual paradigm where high-spectral-efficiency and low-complexity applications are distinguished. This paradigm is exposed in a white paper published in November 2021 [17], from which we have extracted some paragraphs below.

4.1 The physical layer for sub-THz systems

Sub-THz communication systems are considered as a foremost solution to meet the requirements of beyond 5G (B5G) and 6G networks. Some of the contemplated use cases and applications for sub-THz systems are the following:

a) ***High-capacity backhaul***

The envisioned ultra-dense network topology in urban areas or local private networks (e.g., for industry, transport hubs, stadia, or smart cities) with the extreme data-rate, capacity, and latency requirements makes the fiber-based backhauling highly desirable, but sometimes complicated due to current fiber networks penetration (variable from one country to the other) and local installation constraints. The wireless backhaul infrastructure is needed as an alternative or complement to the optical fiber deployment; it offers more agility, shorter installation times, and (in case of a mesh architecture) strong reliability. It may also provide connectivity to mobile or even flying access points. High data-rate wireless backhauling is a valuable competitive technology, which benefits from lower deployment costs and constraints.

b) ***Enhanced short-range hotspot***

An ultra-high data rate downlink serving single/multi-user(s), with end-users complexity and energy constraints. Envisaged applications are short-range hotspots delivering high-speed data to demanding applications such as enhanced Wireless LAN (WLAN), kiosk, augmented or virtual reality, connectivity for robots, drones or autonomous fleets that require sub-ms reactivity.

c) ***Device-to-device communications***

A symmetric high data-rate link with energy and architecture complexity constraints for D2D communications. It includes inter- or intra-chip communications, wireless connectors, or connection between devices in a server farm.

Other use-cases could be envisaged, such as improved physical layer confidentiality thanks to radio confinement and high antenna directivity. Accurate positioning and high-resolution sensing are also strong motivations for the use of the sub-THz spectrum.

Despite the evolution of semiconductor technologies, more research is required to design new physical layer algorithms and transceiver RF architectures to mitigate the severe RF impairments of sub-THz systems.

4.2 Two sub-THz systems paradigms

Figure 5 illustrates the path from the specific sub-THz properties to the proposed paradigm duality: implementation of either a spectral efficient or a low complexity physical layer. Trade-off between spectral efficiency and complexity may also be envisaged for some applications. The recent measurement campaigns have shown that sub-THz propagation channels are largely dominated by a single path (often LoS direct path), which provides most of the energy contribution. It is due to the stronger channel sparsity at those frequencies, in particular in open or urban environments, and to the usage of highly directive antennas, sometimes at both transceiver sides. It follows that single-carrier (SC) communication systems are envisaged to provide low-complexity RF architecture and operate at high-PA efficiency. In particular, sub-THz systems suffer from medium to strong PN impairments, resulting from the poor performance of high-frequency oscillators. The phase impairment severely deteriorates the performance of sub-THz communication systems.

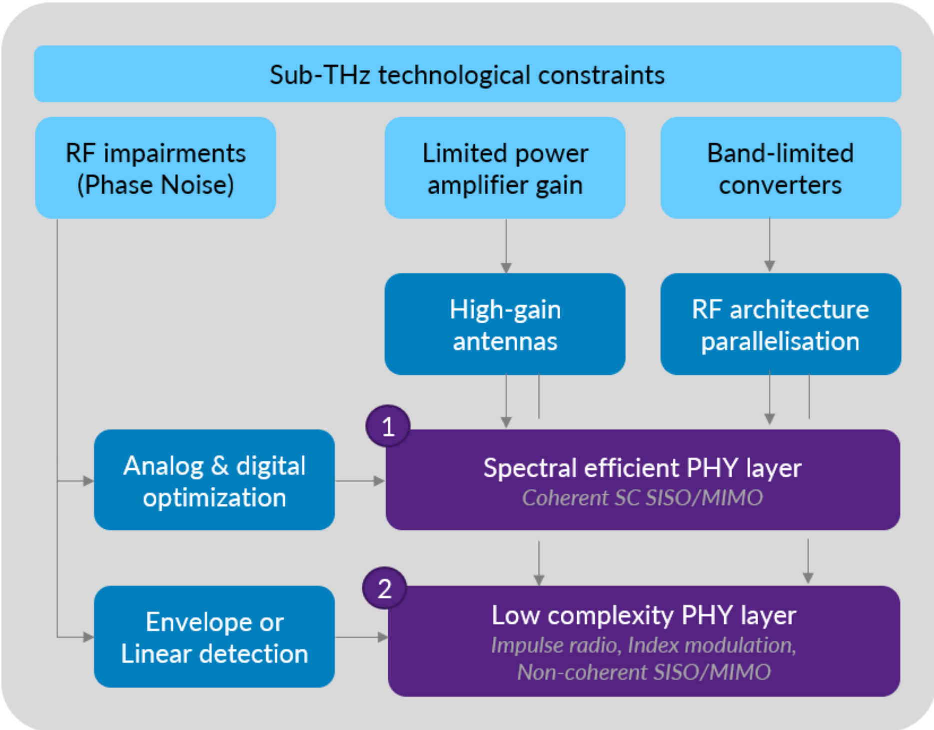

Figure 5: Illustration of the physical layer paradigms for sub-THz communication systems. The constraints coming from the propagation, namely the need for high-gain antenna and beam alignment processing, are common for the two paradigms.

On the one hand, to mitigate the impact of this major RF impairment, the optimization of the signal processing related to physical layer algorithms is mandatory. For example, the optimized modulation and demodulation schemes can be used to achieve some PN robustness. On the other hand, efforts should be done for the design of new oscillator generation techniques compatible with CMOS technology. Last, delivering high power (and relatively high efficiency) with CMOS compatible technologies is still an open research topic. Alternatively, the use of receivers based on envelope or energy detection is also considered, which enables a frequency down-conversion from passband to baseband without the impact of phase impairments.

In addition, the digitalization of large bandwidth signals entails severe constraints on digital-to-analog converters (DAC) and analog-to-digital converters (ADC). The parallelization of the transceiver RF architecture appears to be essential in order to relax the ultra-high sampling rate constraint on converters that are also more power-hungry and costly. Some of the investigated approaches rely on channel bonding systems, *i.e.,* the analog aggregation of multiple carriers.

With regard to the contemplated applications and the presented constraints related to sub-THz communication systems, two paradigms arise for the physical layer: high data rate versus low complexity. We describe in the following paragraphs the features of these two paradigms.

a) ***Spectral efficient physical layer***

Its physical layer corresponds to a communication system whose objective is to maximize the spectral efficiency such as for high capacity back-haul. This physical layer implies the use of in-phase / quadrature (IQ) transceivers, high-quality RF components, and high-order modulation schemes. Concerning the research on the physical layer for such communication systems, most of the current works investigate the optimization of channel bonding systems and the related signal processing.

b) ***Low-complexity physical layer.***

Conversely, in this paradigm, communication systems aim to minimize the complexity of the architecture or the energy consumption to achieve a given rate. Contemplated applications, in this case, are either the enhanced hot-spot or short-range communications. This paradigm entails a complexity/power-limited regime, and hence using a simple RF architecture, analog or basic (e.g., on-off keying) modulation schemes. Numerous research approaches are under investigation for the development of the physical layer for complexity/energy-constrained systems. Research works include the use of index modulation, the design of high data-rate impulse radio, the joint optimization of analog and digital signal processing. It is worth mentioning that Index modulation (IM) provides a relevant solution for power-constrained sub-THz systems, and it also allows to achieve a good trade-off between both paradigms (spectral-efficient and complexity/energy-constrained systems), see [18] and [19].

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