UNOFFICIAL MACHINE TRANSLATION

Grant Thornton

MINISTERSTVO PRŮMYSLU A OBCHODU

Financováno Evropskou unií NextGenerationEU

The development of 6G networks in bands above 100 GHz

Prepared for the Ministry of Industry and Trade

October 2024

Národní plán obnovy

UNOFFICIAL MACHINE TRANSLATION

Grant Thornton

Contents

List of abbreviations and explanations

This overview lists the key abbreviations used in this study. In some cases, abbreviations may appear only once in the text in connection with the explanation of a specific technical feature; their meaning is explained in context and they do not appear in this list.

3GPP	3rd Generation Partnership Project (mobile network standardisation organisation)
5G	Fifth-generation networks
6G	Sixth-generation networks
AAS	Active Antenna Systems
AI	Artificial Intelligence
CBRS	Citizens Broadband Radio Service
CEPT	European Conference of Postal and Telecommunications Administrations
C/I	Carrier-to-Interference
CQI	Channel Quality Indicator (a scaled version of SINR used in modulation selection as an indicator of signal quality)
ČRa	Czech Radiocommunications
D2D	Device-to-Device, Direct-to-Device (term for direct communication between devices, or direct communication to a device in the case of a satellite complement to 6G)
dBm	Decibel-milliwatt (a unit of absolute power level relative to a value of 1 mW)
dBµV	Decibel-microvolt (a unit of absolute voltage level relative to 1 µV)
DL	Downlink (the direction of transmission from the provider to the subscriber)
ECC	Electronic Communications Committee
EDRS	European Data Transmission System
EESS	Earth exploration-satellite service
eMBB	Enhanced Mobile Broadband
ESC	Environmental Sensing Capability
ETSI	European Telecommunications Standards Institute
EU	European Union
FCC	Federal Communications Commission
FDD	Frequency Division Duplex
FSS	Fixed-satellite service
FWA	Fixed Wireless Access
IMT	International Mobile Telecommunications
IoT	Internet of Things
ISS	Inter-Satellite Service
ITU	International Telecommunications Union
LoS	Line-of-Sight (line-of-sight communication)
LPWAN	Low-Power Wide-Area Network
Mbps	Megabits per second
MFCN	Mobile-Fixed Communication Networks

MIMO	Multiple-Input Multiple-Output (system with multiple inputs and outputs)
mMTC	Massive Machine-Type Communications (massive machine-to-machine communications)
ms	Millisecond
MVNO	Mobile Virtual Network Operator
N/A	Not available
NLoS	Non-Line-of-Sight (No direct line of sight)
NR	New Radio (designation for the radio part of the 5G network)
PCI	Physical-Layer Cell Identity (cell identifier)
PPDR	Public Protection and Disaster Relief System
RR	Radio Regulations
RSPG	Radio Spectrum Policy Group
RSRP	Reference Signal Receive Power
SAS	Spectrum Access System
SCS	Subcarrier spacing
SDL	Supplementary DownLink (band for boosting the downlink of other bands)
SINR	Signal-to-Interference-plus-Noise Ratio (signal-to-noise-and-interference ratio)
SRR	Short-range radars
SRS	Space Research Service
SSB	Synchronisation Signal Block for NR (synchronisation sequence)
TDD	Time Division Duplex
TRP	Total radiated power
UAV	Unmanned Aerial Vehicles
U/D	Uplink/Downlink
UL	Uplink
ULS	Universal Licensing System
URLLC	Ultra-Reliable and Low Latency Communications
UTC	Coordinated Universal Time
V2V	Vehicle-to-Vehicle (a term for direct communication between vehicles)
WAS	Wireless Access System
μs	Microsecond

Executive Summary

The aim of this study is to analyse the current state and prospects for the standardisation of 6G networks and to summarise the current state of knowledge regarding the bands above 100 GHz being considered for mobile networks. The study draws on available resources from international standardisation organisations, specialist and scientific articles, as well as the author's own experience. The study comprises three main sections:

- An analysis of 6G networks and their gradual development from 5G through to 5G-Advanced
- An analysis of the potential use of frequency bands above 100 GHz, taking into account their specific characteristics
- A forecast of the potential uses of the band above 100 GHz, an assessment of the benefits, weaknesses and possible licensing methods

Generally speaking, mobile networks are built on the basis of 3GPP standards, the development of which is ongoing. We can expect the 5G-Advanced specification to be finalised in the near future, bringing a range of new features that already point towards the next generation, 6G. A fully-fledged 6G network is likely to be standardised by 2028, with practical deployment and use in a number of countries, including in Europe, expected around 2030.

Frequency bands above 100 GHz, with an upper limit of 1 THz (sub-THz bands), belong to the group of millimetre-wave to sub-millimetre-wave frequencies, which, according to the latest research findings, can be utilised for transmission at ultra-high speeds. This band has been identified as one of the bands for the development of 6G mobile networks after 2030. According to the resolutions adopted at the most recent WRC-23 meeting, all preparatory work, feasibility studies, service coexistence analyses, etc., should be ready for the World Radiocommunication Conference in 2031, which will be crucial for their commercial opening.

Millimetre-wave frequency bands are characterised by a very limited range due to the predominant nature of line-of-sight propagation and high environmental attenuation. This fact, combined with the expected small size of antenna arrays (due to the short wavelengths), will lead to their use primarily for covering interiors and relatively small, confined areas (stadiums, squares, etc.) and for direct communication between devices (D2D, V2V). On the other hand, it will enable far more precise localisation and detection of objects as secondary functions.

In the context of evolving requirements, technological challenges and expected investments (and their return on investment), expansion into bands above 100 GHz does not appear particularly pressing at present and is likely to be necessary only in the long term (after 2040). That is, only after the 26 GHz band – or other bands under consideration that are internationally coordinated for mobile communications – has been utilised and fully exploited.

Possible basic licensing regimes for bands above 100 GHz, as they appear given the current state of knowledge:

- For applications with low radiated power and advanced active antenna systems, it can be tentatively assumed that operating conditions will allow licence-exempt operation (based on a general authorisation) for many 6G applications.
- For specific applications with higher radiated power in situations where the risk of mutual interference between stations would not be acceptable to users, the possibility of granting individual licences will also be considered.

In its conclusion, the study recommends:

- To closely monitor developments in this field and actively contribute to discussions in international forums on the use and licensing of spectrum bands for 6G networks (ITU-R, WRC, RSPG, CEPT).
- To adopt positions in good time and formulate a strategy for the roll-out of 6G networks in the Czech Republic (the appropriate timeframe for formulating this strategy appears to be 2025/26).
- Monitor the utilisation of current spectrum bands, the evolution of customer requirements and the development of services, and, on this basis, update the requirements for utilising spectrum bands above 100 GHz, particularly from the perspective of expected investments and their realistic return on investment.
- Support research and further specialist studies in this area through appropriate calls for proposals and funding mechanisms. In the first phase (approximately 2025 to 2027), the focus should be on theoretical and experimental work carried out by academia and research organisations. In the subsequent phase (approximately 2028 to 2030+), the focus should shift to applied research and collaboration between research organisations and industrial enterprises on specific usage scenarios, as well as the development and testing of specific products and solutions.

Management summary

The aim of the study is to analyse the current state and prospects of standardisation of 6G networks and to summarise the current state of knowledge regarding bands above 100 GHz under consideration for mobile networks. Available resources from international standardisation organisations, professional and scientific articles, as well as the author's own experience, were utilised in the analysis. The study comprises three main sections:

- Analysis of the issue of 6G networks, their gradual development from 5G to 5G-Advanced
- Analysis of the potential for using frequency bands above 100 GHz, taking into account their specific characteristics
- A forecast of the potential for utilising the band above 100 GHz, an evaluation of the benefits, weaknesses and possible licensing arrangements

In general, mobile networks are built on the standards of the 3GPP organisation, the development of which is ongoing. We can soon expect the completion of the 5G-Advanced specification, which will introduce a number of new features heralding the next generation of 6G. A fully-fledged 6G network will likely be standardised by 2028, with practical deployment and use in several countries and across Europe expected around 2030.

Frequency bands above 100 GHz, with an upper limit of 1 THz (sub-THz bands), belong to the group of millimetre to sub-millimetre waves; according to the latest research findings, these are suitable for transmission at ultra-high data rates. This band has been identified as one of the bands for the development of 6G mobile networks after 2030. According to the resolutions adopted at the most recent WRC-23 meeting, all preparatory work, including studies on usability and service concurrency, should be completed in time for the World Radiocommunication Conference in 2031, which will be crucial for their commercial roll-out.

Millimetre-wave frequency bands are typically characterised by a very limited range due to the predominant nature of line-of-sight propagation and high environmental attenuation. This fact, combined with the expected small size of the antenna arrays (due to the short wavelengths), will mean they are used primarily to provide coverage indoors and in relatively small, limited areas (such as stadiums and squares). On the other hand, they will enable much more accurate localisation and detection of objects, as a secondary function.

In the context of the development of requirements, technological challenges and expected investments (and their return), expansion into bands above 100 GHz does not appear to be a pressing issue at present and is only required in the long term (after 2040). That is, only after the 26 GHz band has been utilised and fully exploited, or other internationally coordinated bands under consideration for mobile communications.

Possible basic licensing models in the band above 100 GHz, as they appear at the present state of knowledge, are as follows:

- For applications with low radiated power and advanced active antenna systems, operating conditions allowing licence-free operation (based on general authorisation) can be assumed for many 6G applications.
- For specific applications with higher radiated power, in situations where the risk of unwanted mutual interference between stations would be unacceptable to users, the possibility of granting individual authorisations will also be considered.

In its conclusion, the study recommends:

- Monitor developments in this area closely and actively contribute to the discussion on the use and licensing of spectrum bands for 6G networks (ITU-R, WRC, RSPG, CEPT) in international forums.
- Adopt positions in good time and formulate a strategy for the roll-out of 6G networks in the Czech Republic (2025/26 appears to be a suitable timeframe for its formulation).
- Simultaneously monitor the use of current frequency bands, the evolution of customer requirements and the development of services, and, based on this, reassess the need to use frequency bands above 100 GHz, particularly from the perspective of expected investments and their actual return.
- Support research and other professional studies in this area through appropriate challenges and funding mechanisms. In the initial phase (approximately 2025 to 2027), the focus should be on theoretical and experimental work carried out by academia and research organisations. In the subsequent phase (approximately 2028 to 2030+), the focus should shift to applied research conducted in collaboration between research organisations and industrial enterprises, addressing specific usage scenarios, the development and testing of specific products and solutions.

1 Introduction

The aim of the study is to analyse the current state of 6G network capabilities in the band above 100 GHz, including the definition of the fundamental advantages and disadvantages with regard to application use, spectral characteristics and other factors. Building on the results of work carried out within the ITU and 3GPP, the following will be developed for the Czech Republic:

- An assessment of the characteristics of the band above 100 GHz and their suitability for the development and operation of 6G networks, with an emphasis on range and signal throughput; ensuring the efficient use of the spectrum above 100 GHz and optimising data transmission performance in these frequency bands. Analysis of potential interference and transmission disruption, and the implementation of measures to minimise these issues. Ensuring reliable data transmission under various weather conditions and environments.
- Designing strategies to extend 6G network coverage in bands above 100 GHz, taking into account terrain conditions and potential obstacles.
- Assessing network capacity and the ability to handle the growing number of devices connected to 6G networks in bands above 100 GHz.
- Taking into account the possibilities for backward compatibility with existing 5G networks and procedures for a smooth transition between 5G and 6G networks. Taking into account the subsequent possibility of integrating 6G networks with existing 5G networks and other communications infrastructures.
- Analysing and evaluating current regulatory and standardisation aspects relating to the operation of 6G networks in bands above 100 GHz and ensuring compliance with relevant legislative requirements; licensing and operational requirements. Assessment of the potential impacts of electromagnetic radiation on public health during the operation of 6G networks and the implementation of measures to minimise risks.
- Evaluation of the energy efficiency of 6G networks in bands above 100 GHz and implementation of measures to reduce energy consumption and enhance the sustainability of operations.

The study drew on available resources from international standardisation organisations, specialist and scientific articles, as well as the author's own experience. The study was prepared by experts from the Faculty of Electrical Engineering at the Czech Technical University in Prague in close cooperation with the Czech Telecommunications Office and was consulted with the client on an ongoing basis throughout the drafting process. Preliminary results from studies being carried out in parallel were also utilised, in particular a study focusing on the 26 GHz band.

2 Analysis of 6G network issues

Frequencies ranging from 100 GHz to 3 THz, which have not yet been utilised, are being considered for next-generation wireless communication systems due to their high potential bandwidth. These frequencies may offer scope for applications requiring high data rates, but they also present many new technological challenges and will require advances in the development of equipment, microelectronic circuits, software, signal processing methods, communication control and antenna systems. Alongside the technical challenges and opportunities for wireless communication, there is a growing potential for precise positioning and the tracking of objects and areas.

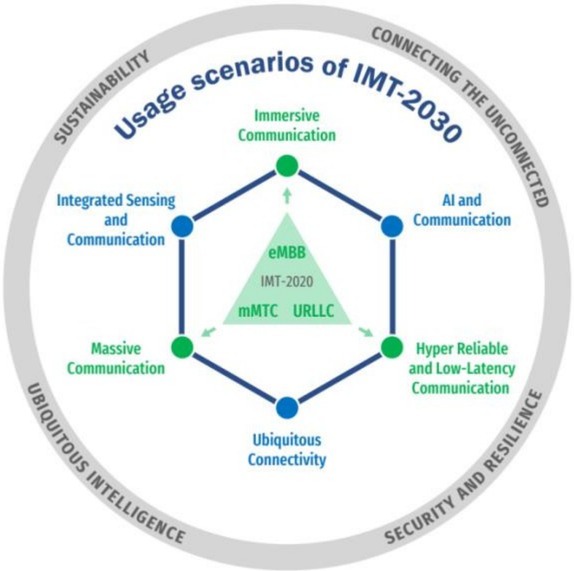
2.1 The Vision for Mobile Telecommunications by 2030 (IMT-2030)

In specifying the current, fifth generation of mobile networks, developers and standardisation bodies have focused primarily on the parallel development of these three segments and areas of application:

1. *Enhanced Mobile Broadband (eMBB*)
2. Ultra-Reliable *and Low Latency* Communication (*URLLC*)
3. Massive machine-*type* communication (*mMTC*)

The following diagram illustrates the transformation of these areas towards future generations of networks (IMT-2030 – the ITU-T's vision for network development towards 2030). Alongside the development of the existing three segments, new challenges are emerging, along with interconnections with areas not entirely directly related to communications as such (sensor technology, AI).

Figure 1: Use cases for IMT-2030 (Source [1])



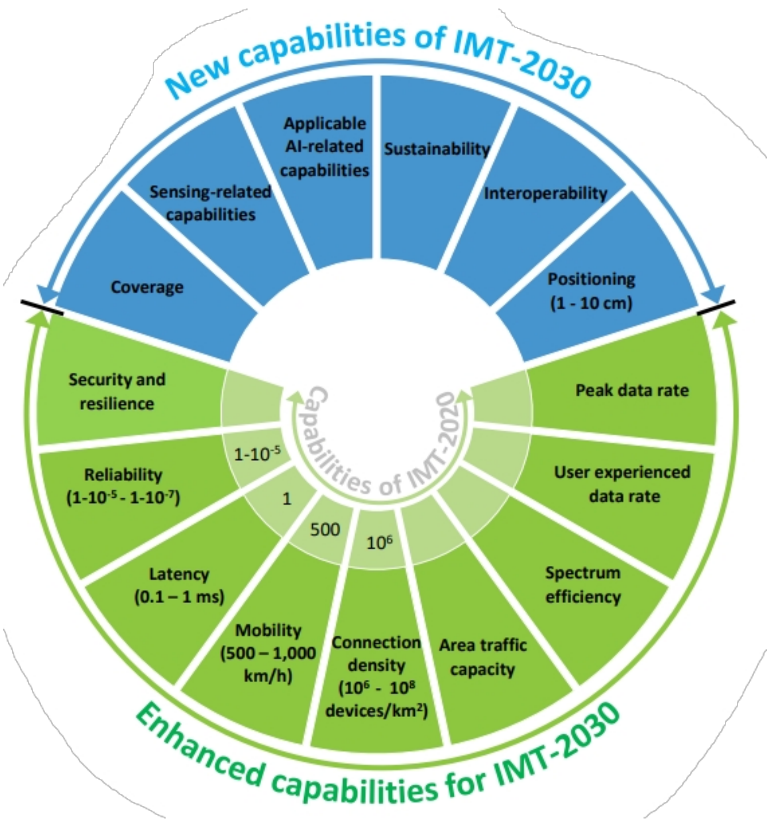
[1] ITU-R Recommendation M.2160-0 (11/2023). Framework and overall objectives for the future development of IMT for 2030 and beyond.

For 6G mobile networks, the target parameters presented in the following table and the accompanying pie chart are set out in comparison with 5G.

Table 1: Target parameters for 6G mobile networks compared with 5G

	5G	6G
Peak data transmission speed:	lower tens of Gbit/s	50, 100, 200 Gbit/s
Commonly available transmission speed:	at least 100 Mbit/s	min. 300/500 Mbit/s
Connection density:	1 million devices per km²	up to 100 million devices per km²
Latency between end devices:	in the order of milliseconds – 10 ms	0.1 – 1 ms
Traffic density:	10 Mbit/s per 1 m²	30/50 Mbit/s per 1 m²
Mobility:	up to 500 km/h	500–1,000 km/h

Figure 2: Key parameters for 6G mobile networks: improvements over 5G (green) and new features compared to 5G (blue, Source[2])



[2] ITU-R Recommendation M.2160-0 (11/2023). Framework and overall objectives for the future development of IMT for 2030 and beyond.

2.2 Key characteristics of 6G

The following overview shows the areas of focus in the development of 6G networks for individual groups of characteristics according to [3]. For illustration purposes, the latest version of the logo and a graphical representation of the key characteristics of 6G networks are provided.

Communication:

- Capacity
- Data rate
- Mobility
- Coverage
- Density of connected devices

AI and computing power:

- Accuracy of results
- AI computation response time
- Computing capacity
- Scalability, adaptability

System reliability

- Security
- Integrity
- Availability
- System recovery time

Integrated monitoring and positioning:

- Scope
- Confidentiality
- Sensing accuracy
- Resolution
- Response time

Energy efficiency:

- Network energy efficiency
- Low CO_2 emissions
- ECO rating
- Battery life

2.3 Development of standardisation from 5G to 6G

Mobile networks are built on the basis **of standards set by the 3GPP[4]organisation** (3rd Generation Partnership Project, 3GPP). The 3GPP organisation continues its work on developing standards from 3G through 4G and 5G to 6G. The specifications take the form of a set of technical standards – a specific version released on a given date, designated as Release 15, 16, and so on. In reality, therefore, these are not revolutionary generational leaps, but a gradual process of innovation (hence the terms 'inter-generational' 5G-Advanced, etc.).

The attached table provides an overview of the latest versions of mobile network standards with their key characteristics.

[3] Taking 5G-Advanced to the next level and bridging into the 6G era, White paper, 2024 Nokia.

[4]https://www.3gpp.org/

Table 2: Overview of the latest versions of mobile network standards[5]

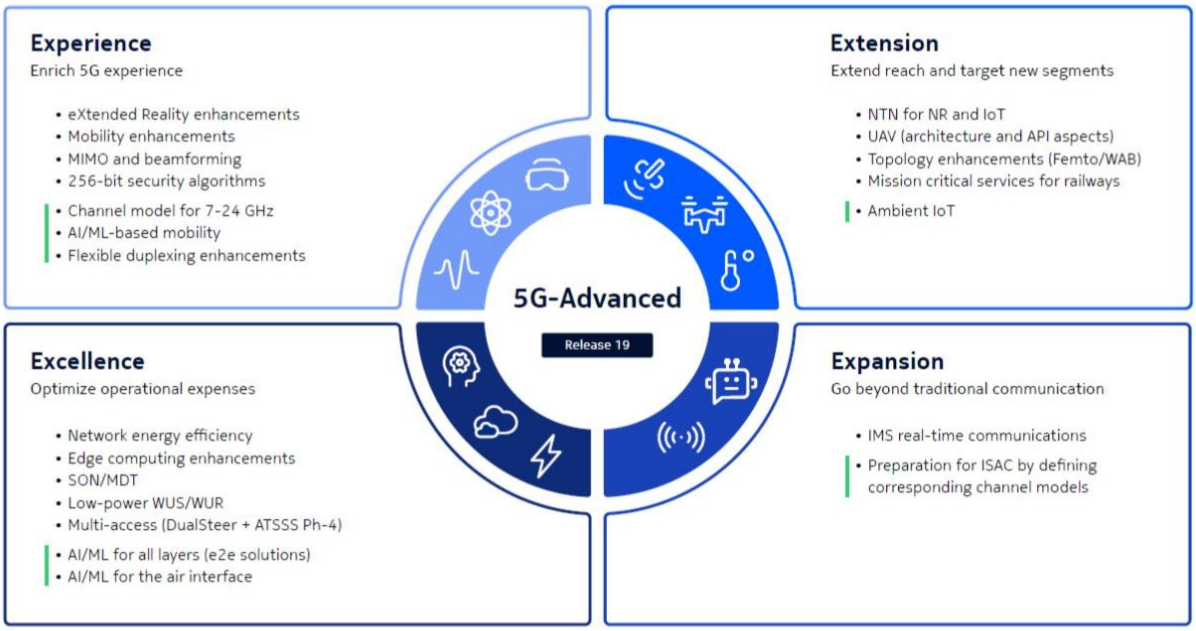
Release 15	Q2 2018	First specification of the 5G NR (New Radio) generation. Support for Vehicle-to-x (V2x) communication, IP Multimedia Core Network Subsystem (IMS) and the Future Railway Mobile Communication System.
Release 16	Q3 2020	5G specifications – Phase 2: 5G enhancements, NR-based access to unlicensed spectrum (NR-U), satellite access.
Release 17	Q1 2022	The TSG RAN (Technical Specification Group Radio Access Network) specifies the development of features that remain important for the overall efficiency and performance of 5G: MIMO, spectrum sharing enhancements, UE power saving and coverage enhancements. Further enhancements to the 5G system and preparation of features to enable new functions and services: non-public networks, the Industrial Internet of Things, low-complexity NR devices, edge computing in 5G, access traffic steering, network automation for 5G, network slicing, advanced V2X services, support for multiple USIMs, proximity-based services in 5G, 5G multicast broadcast services, Unmanned Aerial Systems (UAS), satellite access in 5G, 5G location services, Multimedia Priority Service.
Release 18	Q4 2023	The version designated as 5G-Advanced: Introducing further machine-learning-based techniques at different levels of the wireless network. Edge computing, evolution of the IMS Multimedia Telephony Service, smart energy and infrastructure, vehicle-mounted relays, low-power high-accuracy positioning for industrial IoT scenarios, enhanced access to and support for network slicing, satellite backhaul in 5G.

The extension of the standard to 5G-Advanced was realised with 3GPP Release 18, and we are now taking the next step towards Release 19. Generally, between standard versions, there is usually a refinement of features from previous versions, as well as the addition of new functionalities. The focus will now be on further improvements to energy efficiency, increased coverage and enhanced mobility – but above all on laying the groundwork for a seamless transition to 6G development, including new channel models, expanded full-duplex transmission capabilities, satellite communications, and the development of a framework for the full utilisation of AI/ML (artificial intelligence and machine learning). We expect version 19 to be finalised by the end of 2025, with commercial availability approximately one year after the standard is finalised.

The following diagram provides an overview of the main features of version 19 of the standard, with areas leading towards 6G highlighted.

[5]https://www.3gpp.org/specifications-technologies/releases

Figure 3: Overview of the main features of version 19 of the standard, with areas leading towards 6G highlighted (in green, source [6])



2.3.1 Enhancements to key 5G functions

It is worth noting that several features have already reached a high level of maturity in Release 18 and are not being further developed in version 19. Examples of such features include support for Industrial IoT (IIoT), optimisation for small data transmission (Small Data Transmission – SDT), Multi-SIM, suitability for high-speed trains (High Speed Train – HST), dynamic spectrum sharing (Dynamic Spectrum Sharing – DSS), In-Device Coexistence (IDC) and dual connectivity using carrier aggregation (Dual-Connectivity / Carrier Aggregation – DCCA). This does not, however, mean that development in these areas has been completed; it is likely that this current state will be built upon and further developed in a subsequent version of the standard.

In the following paragraphs, we outline the features of version 19 that are significant for 5G-Advanced and take standardisation a step further.

2.3.1.1 Enhanced mobile network support for extended reality (eXtended Reality – XR)

These improvements are aimed, on the one hand, at the consumer sector in the form of multimedia support for real-time extended reality (RXRM) and, on the other hand, at industry to support work activities. First and foremost, this involves the use of 360° video and spatial 3D audio, which necessitates high data transfer rates combined with low latency. At the same time, however, the standard also addresses energy efficiency in user devices tailored to XR operations, which are generally demanding in terms of the volume of data transmitted and processed (and therefore place high demands on processor computing power and, consequently, its power consumption).

Specific system measures relate to radio resource management (RRM), the expansion of multimodality, and a newly conceived classification of individual data streams into different quality of service (QoS) classes, along with the associated signalling between terminals and the base station, and between the base station and the network core.

2.3.1.2 MIMO Improvements

The ongoing development of MIMO (Multiple-Input, Multiple-Output) multi-channel transmission is intended to ensure even higher capacity and stable data communications whilst on the move. The main ambition is to advance the technology to support up to 128 transmit ports. Current plans envisage

---

[6] Taking 5G-Advanced to the next level and bridging into the 6G era, White paper, 2024 Nokia.

64 transmit ports, which will ensure approximately 20–40 per cent higher spectral efficiency compared with solutions commonly used today, whilst 128 ports, once development is complete and the technology moves into the commercial phase, will bring further improvements. Improvements utilising multi-TRP (transmit receive point) are also planned.

2.3.1.3 Mobility improvements

Mobility based on cooperation between the physical layer (PHY / L1) and the medium access control layer (MAC / L2) was already introduced in Release 18 as lower-layer-triggered mobility (L1/L2 Triggered Mobility – LTM). It involves the rapid switching between serving base stations. This procedure helps, in particular, to reduce the interruption time during a handover to just 10–20 ms, but will also bring a number of other improvements. The LTM concept is being further developed and will be implemented in version 19.

2.3.1.4 Improving energy efficiency

Energy efficiency (EE) remains a key objective in ensuring long-term sustainability. Features supporting energy-efficient network operation have long been in use and include, for example, cell activation/deactivation and dynamic device power management. As the radio access network (RAN) is the most energy-intensive component, the main efforts to save energy are focused particularly on this area.

One approach is a more dynamic exchange of signalling messages, which will enable faster feedback from user terminals. Artificial intelligence and machine learning (AI/ML) applied in the field of energy efficiency will play an important role. The aim is to predict user behaviour, terminal movement, etc., in order to plan radio resources (and thus the energy required to power them) more efficiently. The objective is to meet requirements whilst minimising resource usage without negatively impacting the user experience when using the service.

This is also linked to the introduction of a wake-up mechanism for low-power devices (wake-up signal), particularly to support IoT devices such as industrial sensors, which was also developed in version 18. Version 19 is expected to include the final specification of the corresponding solutions (Idle and Inactive modes) and signalling (Lower Power Synchronisation Signal – LP-SS).

2.3.1.5 Satellite connectivity

It has long been anticipated that satellite connectivity will complement terrestrial networks in providing truly global coverage. 3GPP introduced solutions for non-terrestrial networks (NTN) as early as Release 17. However, it is only Release 19 that will include solutions enabling base station functions to be deployed on satellites. The aim is to improve performance and reduce latency, including support for NTN IoT applications.

2.3.1.6 Features to support UAVs and UAM

For several years now, 3GPP has been working intensively on mobile network support for the operation of unmanned aerial vehicles (UAVs). There is also growing interest in Urban Aerial Mobility (UAM), which aims to provide sustainable air transport for both passengers and cargo in urban environments, either via remotely piloted vehicles or those with a pilot on board.

In order to meet the requirements of aviation forums, 3GPP Release 19 will investigate how the Network Exposure Function (NEF) block can be extended to support interactions between mobile operators and UAV Traffic Management (UTM), for example for pre-mission flight planning and in-flight tracking during a mission. Mechanisms for detecting and avoiding airborne vehicles (Detect and Avoid – DAA) will be studied. The focus will be on improving the application layer architecture for real-time monitoring of UAV connection status, as well as on supporting direct communication between UAVs in the same area, whilst ensuring communication redundancy and high service reliability.

2.3.1.7 Architecture and Operational Efficiency

Mobile network standards are constantly evolving, including in the area of features that help operators achieve greater efficiency in the management and operation of networks and services. A set of features for self-organising/optimising networks (Self-Organising/Optimising Network – SON)
and Minimisation of

Drive Test – MDT) will continue to be developed in version 19 to enable support for new features introduced in version 18. For example, version 19 will cover mobility robustness optimisations (MRO), including conditional handover to selected Secondary Cell Groups (SCG). The specifications will require the expansion of the exchange of new inter-node information and improvements to reports from terminals for tuning mobility parameters. SON/MDT enhancements will help improve the operational efficiency of 5G-Advanced and facilitate the deployment of new features in the network.

Further improvements will be made to IMS (IP Multimedia System) and its communication data channel. These improvements are expected to offer operators new business opportunities, enabling them to make network functions available to application service providers and to make new applications (e.g. games) available to end users.

Release 19 will further enhance the use of edge computing. It will reduce the impact on 5GC control plane functions for the Edge Hosting Environment (EHE) and introduce further optimisations for the Edge Application Server (EAS).

2.3.1.8 Enhanced security

Quantum computers pose a long-term threat to information security, not only for current data but also for historical data that may have been collected for future decryption. Consequently, the implementation of mechanisms with a 256-bit key length is also being prepared for mobile networks. The algorithms are to be developed and evaluated by the ETSI SAGE (Security Algorithms Group of Experts) at the request of 3GPP. Version 19 aims to publish 256-bit algorithms for the network's radio interface. In addition to algorithms for protecting confidentiality and integrity, a mode of Authenticated Encryption with Additional Data (AEAD) should be introduced.

2.3.1.9 Topological improvements

In Release 19, two network topologies will be finalised for standardisation: 5G femtocells and Wireless Access Backhaul (WAB). 5G NR femtocells can be used to improve indoor 5G coverage and to offload traffic from the macro network. Work on femtocells will include access control mechanisms and a method for enabling access to local services from a privately operated femtocell. Femtocell equipment should operate in plug-and-play mode, whilst the femtocell owner must retain control over the group of users who may use it. The WAB function relates to the operation and the use of mobile base (retransmission) stations in vehicles, typically public transport (buses, trains), and their coordination with the standard network of fixed base stations.

2.3.1.10 Support for critical services for rail transport

The expansion of support for mission-critical services for railways is being progressively incorporated within the 3GPP specifications. The aim is to respond to the current requirements of railway operators (International Union of Railways) and to realise the vision of the Future Railway Mobile Communication System (FRMCS) as a replacement for and successor to the GSM-R system, including interoperability. The RAN specification, as early as Release 18, recommends dedicated spectrum in the 2.7 GHz band for migration from GSM-R to FRMCS. The aggregation of multiple carriers, including those from other bands, will be specified in Release 19, thereby achieving the full RAN functionality required for critical railway communications and signalling.

2.3.2 The 5G-Advanced update leading towards 6G

5G-Advanced will also be an important preparatory step towards 6G in several technical areas, as will be described in more detail in the following paragraphs.

2.3.2.1 Extensive use of AI/ML

An extensive study of AI/ML methods and algorithms for the lower layers of the radio interface (PHY and MAC) was already carried out in Release 18. It focused on the use of CSI compression/prediction, positioning and beam steering. The use of AI/ML will be standardised in Version 19, including a generic framework to support AI/ML for one-sided models – i.e. models that are trained either by the terminal or by the base station. This framework will enable end-to-end ML management, performance tracking, data collection and monitoring, feature selection, activation and deactivation, switching, and a return to conventional operation. Among other things, this will ensure that AI/ML does not result in degradation of performance, which could occur, for example, due to insufficient training for certain scenarios.

Release 19 will also include a new AI/ML-based mobility study focusing on handover optimised for the L3 layer, with the aim of improving overall mobility performance and enhancing the end-user experience with services and application operation. At the network level, AI/ML will serve, amongst other things, to improve energy efficiency.

The 3GPP SA6 working group, responsible for applications and critical communications, will focus on supporting an additional application layer enabling the systematic use of AI/ML. This includes support for upcoming modules, including the Vertical Application Layer (VAL), and the transmission and distribution of training data. The plans also include a potential study into whether and how data from digital twin modelling on the network side could be utilised as part of the AI/ML lifecycle. Together, these activities represent support for AI/ML at all layers of communication and across the entire mobile network infrastructure, encompassing the RAN (radio access network), CN (core network) and management layers. The result should be improved performance for end users, optimisation of overall network performance, more efficient operation, and easier deployment of new features and services.

2.3.2.2 Channel modelling for new bands and new applications

At the ITU World Radiocommunication Conference 2023 (WRC-23), it was agreed to address the allocation of a new portion of licensed spectrum for mobile communications in the 7–15 GHz band (specifically the 7.125–8.4 GHz and 14.8–15.35 GHz bands under consideration), which have the potential to provide increased transmission capacity compared to currently used bands. As part of the preparations for their use, it is necessary to verify the current radio channel model used by 3GPP and, where appropriate, propose refinements or extensions so that it fully reflects the effects of signal propagation in these bands.

Another area where channel modelling studies will be carried out is the support for Integrated Sensing and Communication (ISAC). This may in future enable the use of new 'tracking-as-a-service' applications, where radio signals are utilised not only for transmitting information but also for detecting and tracking spaces and objects, such as UAVs, vehicles, and hazardous objects on roads and railways. A prerequisite for this is having reliable and spatially consistent radio channel models that enable the modelling and differentiation of the radio characteristics of both desired and unwanted objects.

2.3.2.3 IoT devices utilising ambient energy

Version 18 included an initial study of the Internet of Things utilising ambient energy (Ambient IoT). Unlike earlier IoT systems, Ambient IoT devices have very limited power supply and energy storage capabilities; however, a major advantage is that they do not require battery replacement or external recharging. Proposed applications include tracking objects for logistical purposes, and this essentially represents an extension of existing RFID systems (so-called passive tags) over greater distances. The study has reached the preliminary conclusion that the Ambient IoT concept is feasible and beneficial; therefore, a further working group will develop the solution as part of Release 19. At the same time, the work needs to be coordinated with other groups, namely RAN and SA, including the system architecture. The plan is to utilise the FR1 bands (frequency range up to 7.125 GHz) in licensed spectrum mode with frequency division duplex (FDD). Two types of devices will be supported:

- Devices with a peak power consumption of approximately 1 μW, featuring energy harvesting but without downlink data transmission.
- Devices with a maximum power consumption of several hundred μW, featuring energy harvesting and utilising both transmission directions.

An important part of the project will be detailed performance studies, both in terms of power supply and radio transmission balance, as well as studies on the coexistence of devices with one another.

2.3.2.4 Flexible duplex transmission modes

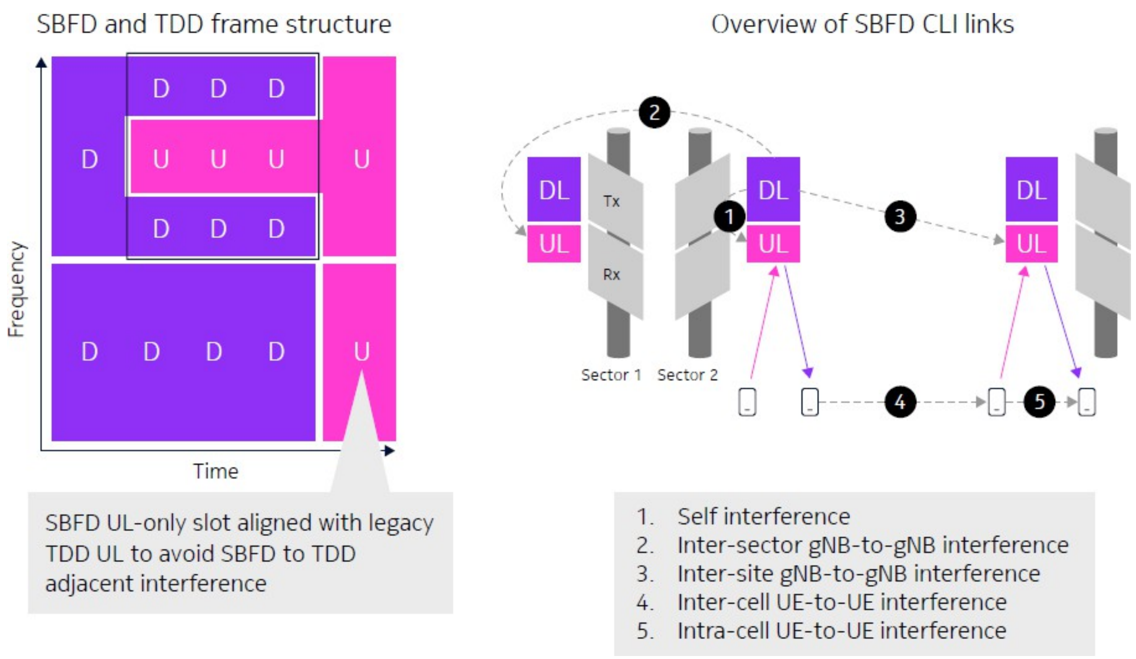
In Release 18, the 3GPP group launched an extensive study of more flexible duplex methods for unpaired bands. This included an assessment of the performance and potential of time-division duplex (TDD) as well as the sub-band full-duplex (SBFD) method. The motivation for this is to achieve better coverage, capacity and latency for the uplink, so as to enable more flexible configuration of radio resources, albeit at the cost of more complex procedures and signalling to ensure coexistence. The SBFD method allows simultaneous uplink and downlink transmissions at any given moment on different frequencies (selected sub-bands) allocated from the total available frequency band, enabling faster response times and data exchanges compared with the TDD method, which allows the entire available band (time slot) to use the entire available bandwidth exclusively for either the uplink or the downlink.

The research focuses in particular on coordination algorithms and mechanisms to mitigate interference. However, the design of radio interfaces for SBFD entails additional costs and greater complexity, as it requires the implementation of tunable RF filters at the receiver input to suppress both self-interference and external interference. The coexistence of adjacent channels used by different operators in SBFD mode must also be investigated. It is likely that SBFD will only be successfully deployed in practice as part of the 6G standard, given the tasks and challenges outlined above that need to be resolved.

The figure below shows, on the left, a schematic representation of the frame structure for two neighbouring base stations with time slots for the uplink (U, UL) and downlink (D, DL) directions. On the right is a schematic diagram of a base station with two sectors, another base station and mobile terminals (UE). Below these, the potential sources of interference between signals are numbered; these must be eliminated to maximise transmission performance:

1. Self-interference between the transmitter and receiver – reduced by the design and a guard interval between transmission directions.
2. Interference between the transmitter and receiver of different sectors of the same base station – reduced by the design, optimisation of time slot allocation and an automatic transmit power limitation system.
3. Interference between the transmitter and receiver of different base stations – reduced by the design, optimisation of time slot allocation and an automatic transmit power limitation system.
4. Interference between the transmitter and receiver of terminals connected to different base stations – reduced by the design, optimisation of time slot allocation and an automatic transmit power limitation system.
5. Interference between the transmitter and receiver of terminals connected to the same base station – reduced by design and a guard interval between transmission directions.

Figure 4: Illustration of flexible resource allocation options for both transmission directions (Source[7])



2.3.3 Summary of the differences between 5G and 6G networks

Further advances in real-time communication

- Improved support for the IMS data channel
- Sufficient performance for end-to-end (E2E) XR
- Management solutions for end-to-end XR, including capacity expansion and improved QoS support

AI/ML across all layers of communication

- Deployment of AI/ML for both the radio interface and the network core, including efficient training, data management and ensuring trustworthiness

Improved energy efficiency

- A more efficient radio interface optimised for power-saving modes, including associated AI/ML algorithms
- Providing a framework for reducing network infrastructure energy consumption

Architectural and operational improvements

- Enhancements for SON / MDT, Edge Cloud, IMS data channel, femtocells, WAB, etc.

MIMO and mobility

- Support for 64 (128) channels
- Improved radio beam control
- More robust mechanisms to support mobility and reduce handover times

Flexible duplex modes

- Improved uplink coverage and reduced latency for unpaired bands

[7] Taking 5G-Advanced to the next level and bridging into the 6G era, White paper, 2024 Nokia.

- Introduction of dynamic TDD and the SBFD concept

Ambient-powered IoT devices

- Research into ultra-low-power IoT devices and their powering via ambient radio energy (Ambient IoT)

Channel modelling for new use cases

- Channel models suitable for tracking objects in the vicinity
- Models for the 7–24 GHz band

NTN and UAVs

- Support for collaboration with the satellite sector, including IoT
- Enhancements for UAVs with support for traffic management and coordination

Topology enhancements

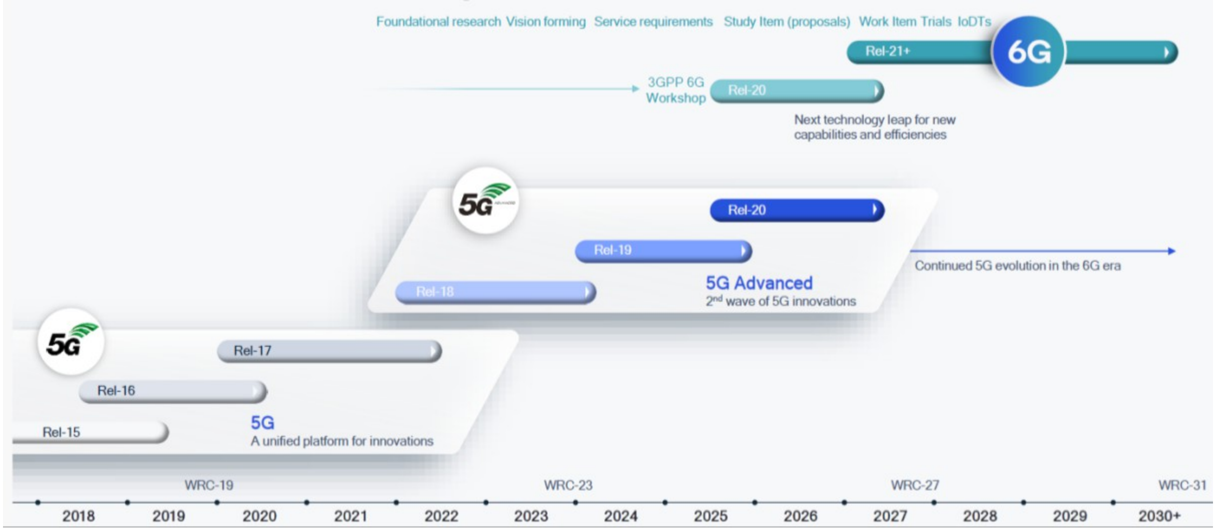
- RAN enhancements to support 5G femtocells

256-bit security algorithms

- Enhanced security for the radio interface

The following diagram shows the timeline of the gradual steps in the transition from 5G, through 5G-Advanced, to 6G. It is clear that, according to the plan, the full 6G version of the standard (Release) will be numbered 21, with an expected release in 2028.

Figure 5: Timeline of the phased transition from 5G, through 5G-Advanced, to 6G (Source [8])



[8] @QCOMResearch, 3GPP roadmap towards 6G, CEPT Workshop on 6G Mobile Communications, 30 June 2023

3 Use of frequency bands above 100 GHz

Bands above 100 GHz are not currently in widespread use for communications. A significant portion of this spectrum is allocated to passive radio astronomy services, passive Earth observation satellite services and passive space research services.
The conditions for mobile or other communications networks are not expected to be defined until the World Radiocommunication Conference in 2031. Until then, research, experiments and discussions will continue within the specialist community.

3.1 Allocation of bands above 100 GHz

According to the National Frequency Table – Decree on the Frequency Band Allocation Plan[9]– the following types of waves are concerned. Current considerations include bands extending to frequencies of just over 300 GHz, and potentially up to 1 THz (sub-THz bands) in the future.

Table 3: Designations of wave types with extremely short wavelengths

Band number N	Symbols	Frequency range	Corresponding band names
11	EHF	30 to 300 GHz	millimetre
12	---	300 to 3,000 GHz	decimetre

Transmissions in a number of sub-bands above 100 GHz are currently prohibited, as they are allocated to the passive Earth exploration satellite service and the space research service: 100–102, 109.5–111.8, 114.25–116, 148.5–151.5, 164–167, 182–185, 190–191.8, 200–209, 226–231.5, 250–252 GHz.

Certain additional conditions are specified, for example:

- The 122–123 GHz band (centre frequency 122.5 GHz) and the 244–246 GHz band (centre frequency 245 GHz) are designated for industrial, scientific and medical (ISM) purposes.
- In the 105–109.5 GHz, 111.8–114.25 GHz and 217–226 GHz bands, use is restricted solely to radio astronomy conducted in space.
- In those parts of the 275–450 GHz range that are used by radio-astronomical applications, conditions (e.g. minimum separation distances or exclusion angles) may be established on a case-by-case basis to ensure the protection of radio-astronomical observatories from terrestrial mobile or fixed service applications.
- The use of spectrum in the 275–1000 GHz band by passive services does not preclude the use of this spectrum by active services.
- All frequencies in the 1000–3000 GHz band may be used by both active and passive services.

The practical use of bands above 100 GHz for 6G and higher-generation mobile networks is the subject of research and will, in the future, require an update to the National Frequency Table, based on the outcomes of international coordination activities. These take place at regular four-year intervals as part of the World Radiocommunication Conferences, the most recent of which was held in 2023 (WRC-23).

[9] Decree No. 105/2010 Coll.

Resolution No. 255[10]was issued concerning the band in question.It states that, in view of global requirements for the development of mobile telecommunications services, requirements for various usage scenarios and applications—such as improved high-speed mobile connectivity, intensive communication with a large number of dispersed devices (sensors) and extremely reliable, low-latency communication, larger contiguous blocks of spectrum than those currently available in the frequency bands will be required (from 2030 onwards).

It is therefore necessary to complete studies on usability, sharing with other services, etc., well in advance, so that final conclusions can be adopted at the World Radiocommunication Conference in 2031, taking into account the technical and operational characteristics of terrestrial IMT systems, including advances in technology and spectral efficiency, anticipated deployment scenarios for IMT-2030 systems and related requirements for high data traffic, as well as the protection of services to which the frequency band is primarily allocated. These are the following bands: 102–109.5 GHz, 151.5–164 GHz, 167–174.8 GHz, 209–226 GHz and 252–275 GHz.

This resolution is followed by Resolution No. 721[11], which concerns the adjacent 275–325 GHz frequency band.

All preparatory work, feasibility studies, service coexistence analyses, etc., for the specified bands should be finalised in time for the 2031 World Radiocommunication Conference.

3.2 Characteristics of bands above 100 GHz

Radio communications in the sub-THz bands offer the potential for high transmission capacity for data services, thanks to the large amount of continuously usable bandwidth, which can be utilised in various applications. However, the use of these frequency bands is strongly influenced not only by the laws of physics (electromagnetic wave propagation) and the geometry of the hardware itself (e.g. the shape and dimensions of antennas), but also by the limited performance of current signal processing circuits.

These physical laws are reflected in the power balance of the radio link, which will significantly influence the primary requirement for high transmission speeds in these networks. This primarily concerns the minimum power levels at the receiver input and uniform attenuation across the entire transmission bandwidth (this can be compensated for based on knowledge of the transmission channel parameters). To achieve the minimum required power level at the receiver end, the following parameters can be adjusted within the power balance for a given distance and frequency: transmitted power level, transmit antenna gain, and receive antenna gain.

From the perspective of electromagnetic wave propagation in the sub-THz bands, it is necessary to select frequency bands where attenuation by oxygen (O_2) and water (H_2O) molecules is minimal. Frequency bands of approximately 80–100 GHz, 140–160 GHz and 220–240 GHz appear to be promising. However, even here there will be significant free-space attenuation, which is directly proportional to the square of the frequency and the square of the distance. This has a significant impact on the power balance of the radio link.
Another characteristic of these frequencies is the shallow penetration depth of electromagnetic waves into materials (low penetration through obstacles); when electromagnetic waves interact with materials, reflections and scattering occur at the air–material interface. We shall discuss some of these properties and limitations in more detail below. The usability of the band above 100 GHz is addressed not only in a relatively large number of scientific articles but also in the ITU-R summary report [12].

3.2.1 Environmental attenuation

When considering the use of higher frequency bands, it is essential to take into account, first and foremost, the increase in free-space propagation loss. When shifting communications from the commonly used mobile communication bands in the order of a few GHz to bands in the hundreds of GHz – i.e. to frequencies a hundred times higher – free-space propagation loss increases by 40 dB. At higher frequencies, this increased attenuation can be compensated for by high-gain antennas, which concentrate the radiated power into a narrower angular beam. This will differ from today's typical base station antenna solutions, which use antennas covering a 120° transmission sector (typically 3 sectors, i.e. 3 antennas per cell).

Of course, there are several options for implementing high-gain antennas, but feasibility in the range of hundreds of GHz is not always straightforward, partly due to the need to meet the requirements of broadband operation. For example, antennas consisting of a phased array

---

[10] RESOLUTION 255 / WRC-23: Studies on frequency-related matters for International Mobile Telecommunications (IMT) identification in the frequency bands [102–109.5 GHz, 151.5–164 GHz, 167–174.8 GHz, 209–226 GHz and 252–275 GHz] for the future development of IMT

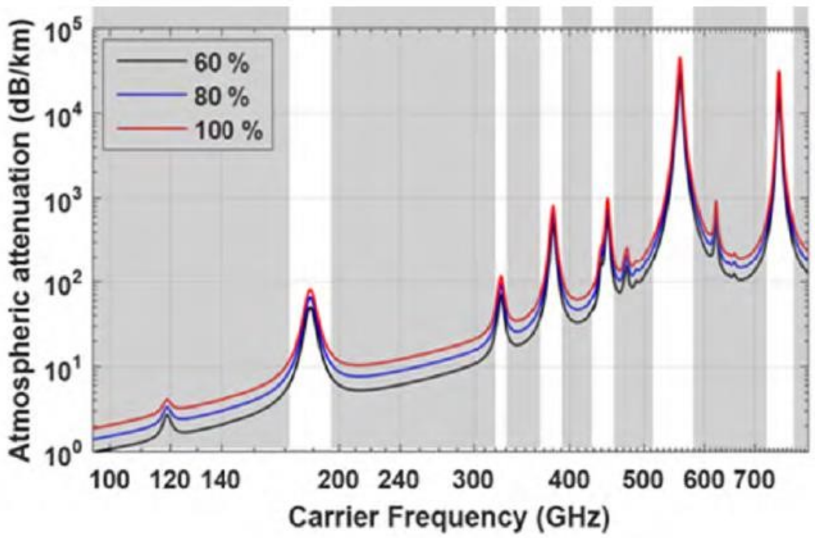
[11] RESOLUTION 721 /WRC-23: Studies on potential new allocations to fixed, mobile, radiolocation, amateur, amateur-satellite, radio astronomy, Earth exploration-satellite (passive and active) and space research (passive) services in the frequency range 275–325 GHz

[12] Report ITU-R M.2541-0 (05/2024): Technical feasibility of IMT in bands above 100 GHz

These technologies are well established at lower frequencies. This approach, which is also used in 5G systems, becomes more challenging when designing systems with wider sub-bands[13] .

A second important difference between low and high frequencies is atmospheric attenuation. Losses are caused by absorption, which increases gradually and is further manifested in the form of several spectrally narrow absorption peaks, as shown in the following graph, typically in the regions of 183 GHz, 325 GHz, 380 GHz, 450 GHz, 550 GHz and 760 GHz. However, it is possible to allocate sufficiently wide bands for communication between these absorption peaks[14] .

Figure 6: Graph illustrating the frequency dependence of the additional attenuation caused by the passage of an electromagnetic wave through the atmosphere for various relative humidities of the environment [15][16]



However, even in areas with high attenuation, systems capable of very short-range communication (several tens of metres) and secure communication can operate (the attenuation prevents interference or potential eavesdropping from a greater distance). Nevertheless, a fairly large portion of the spectrum up to almost 300 GHz exhibits additional attenuation of less than 10 dB/km. These frequency bands can be used for high-speed 6G mobile wireless networks with a coverage range of up to 1 km, and possibly even further. A large part of the spectrum between 600 and 800 GHz, however, exhibits extreme attenuation of 100 to 200 dB/km, which, if utilised, would necessitate reducing the cell radius to 100 m. However, it is reasonable to anticipate the development and use of electronically steered directional antennas with very high gain, which will be compact in size and are likely to enable more efficient utilisation of even such high-frequency bands[17] .

Modelling of environmental attenuation is covered in ITU-R Recommendation P.676-13[18] .

It is well known that hydrometeors, such as rain, fog droplets, snow and hail, cause significant attenuation at frequencies above 10 GHz. For example, signals in the 73 GHz band are attenuated by 10 dB/km at a precipitation intensity of 50 mm/h. Interestingly, as the frequency increases from 100 GHz to 500 GHz, rain no longer causes any extreme increase in attenuation, as can be seen from the following graph. For

---

[13] T. S. Rappaport et al., "Wireless Communications and Applications Above 100 GHz: Opportunities and Challenges for 6G and Beyond," in IEEE Access, vol. 7, pp. 78729–78757, 2019, doi: 10.1109/ACCESS.2019.2921522

[14] Josep M. Jornet, Edward W. Knightly, Daniel M. Mittleman: Wireless communications, sensing and security above 100 GHz. Nature Communications | (2023), https://doi.org/10.1038/s41467-023-36621-x. https://www.nature.com/articles/s41467-023-36621-x

[15] T. S. Rappaport, J. N. Murdock, and F. Gutierrez, Jr., ‘State of the art in 60-GHz integrated circuits and systems for wireless communications’, Proc. IEEE, vol. 99, no. 8, pp. 1390–1436, Aug. 2011.

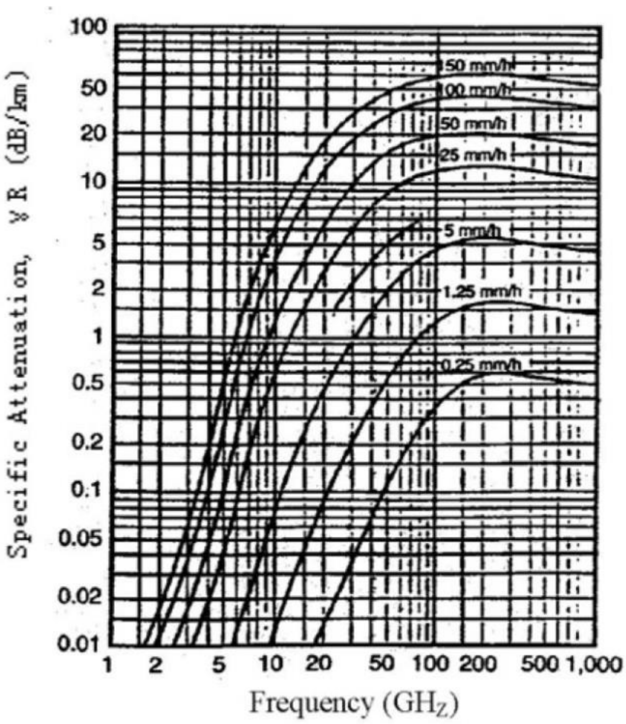
[16] J. Ma, R. Shrestha, L. Moeller, and D. M. Mittleman, ‘Invited article: Channel performance for indoor and outdoor terahertz wireless links’, APL Photon., vol. 3, no. 5, Feb. 2018.

[17] Josep M. Jornet, Edward W. Knightly, Daniel M. Mittleman: Wireless communications, sensing and security above 100 GHz. Nature Communications | (2023), https://doi.org/10.1038/s41467-023-36621-x. https://www.nature.com/articles/s41467-023-36621-x

[18] ITU-R Recommendation P.676-13 (08/2022): Attenuation by atmospheric gases and related effects

For anticipated cell sizes in urban areas in the lower hundreds of metres, the effect of hydrometeors can be compensated for by an appropriate antenna gain (achievable by shaping the antenna beam with multiple elements)[19] .

Figure 7: Frequency dependence of attenuation in dB/km caused by precipitation of a given intensity in mm/hour[20][21]



Contrary to older conventional wisdom, it is now becoming apparent that the atmosphere is not impenetrable to signals in the 100–1000 GHz band, provided that attenuation peaks caused by absorption are avoided. It can be assumed that directional, electronically steerable, high-gain antenna arrays will enable mobile communications up to 1 THz, where attenuation levels previously thought to be insurmountable can be overcome. It should be noted, however, that all active communication services utilising frequencies above 100 GHz must be designed so as not to interfere with the significant existing community of passive monitoring for astronomical purposes and Earth observation. Highly directional antennas can help achieve this, but further research is needed to establish interference limits or assess the impact of antenna side lobes in order to prevent interference with geostationary satellites.

3.2.2 Signal propagation

Research is still being conducted into the propagation of signals above 100 GHz in built-up areas and the influence of various building materials. In these frequency bands, it is also necessary to address the influence of, for example, surface roughness and the corresponding scattering parameters. Many more measurements in urban, suburban and rural areas under various conditions will need to be carried out to study the channel characteristics and subsequently model them (estimate the parameters)[22] .

In a typical indoor environment, conventional wireless systems operate at frequencies where absorption is low for many materials and where many surfaces are smooth compared to the (longer) wavelength. It is generally assumed that between the transmitter and the receiver, multipath propagation occurs with a multitude of signal paths, so that the reception at any given location consists of the superposition of many waves with different delays. In contrast, the wireless channel at frequencies close to 1 THz is entirely different. Typically, the propagating wave is attenuated by a much higher loss, and interactions with most surfaces do not result in sufficiently significant reflections. As a result, both indoor and outdoor environments are usually much ‘sparser’, and fewer signal paths connect the transmitter and receiver.

---

[19] T. S. Rappaport et al., "Wireless Communications and Applications Above 100 GHz: Opportunities and Challenges for 6G and Beyond," in IEEE Access, vol. 7, pp. 78729–78757, 2019, doi: 10.1109/ACCESS.2019.2921522

[20] T. S. Rappaport, J. N. Murdock, and F. Gutierrez, Jr., ``State of the art in 60-GHz integrated circuits and systems for wireless communications,'' Proc. IEEE, vol. 99, no. 8, pp. 13901436, Aug. 2011.

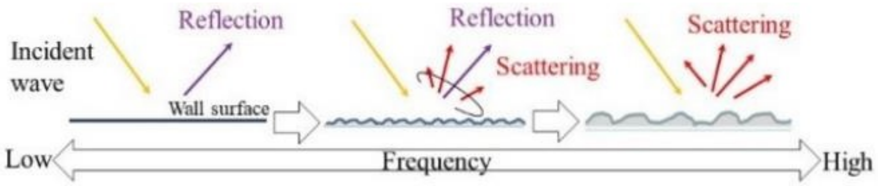
[21] Z. Qingling and J. Li, ‘Rain attenuation in millimetre-wave ranges’, in Proc. 7th Int. Symp. Antennas, Propag. EM Theory (ISAPE), Oct. 2006.

[22] T. S. Rappaport et al., “Wireless Communications and Applications Above 100 GHz: Opportunities and Challenges for 6G and Beyond,” in IEEE Access, vol. 7, pp. 78729–78757, 2019, doi: 10.1109/ACCESS.2019.2921522

Furthermore, due to the 'opacity' of many objects, including people, line-of-sight (LOS) paths are usually blocked, which can pose a problem for maintaining connectivity. However, given the millimetre wavelength, the situation is not as dramatic as with optical radiation. Diffuse scattering from rough surfaces can, in many cases, be utilised to maintain the connection, albeit with a lower signal-to-noise ratio.

The diagram below illustrates how the same surface (a wall covered with plaster and paint) appears from the perspective of signals with different wavelengths. For wavelengths that are significantly longer than the surface irregularities (grains in the plaster and paint), the surface appears smooth and reflections occur primarily off the wall's surface. Conversely, for wavelengths that are shorter and comparable to the surface roughness, the signal is scattered into the immediate surroundings.

Figure 8: Frequency dependence of reflection and scattering, as observed for the same material (wall surface) at different frequencies[23]



Part of the signal penetrates from outside into the interior of buildings, which is very important for indoor reception of mobile network signals, including reception inside vehicles (trains, buses). However, as the frequency increases, the signal intensity decreases, so higher frequencies are generally not suitable for indoor coverage. This problem can be solved by signal repeaters or by installing indoor base stations in the form of femto- and pico-cells.

Attenuation values vary depending on the construction materials used in buildings (glass panes, brick walls, reinforced concrete or steel structures). Comparisons for glass (standard, uncoated) and an external wall (brick with plaster) are shown in the following tables for three different frequencies. The rows show different wave polarisation (V/H) and the columns show both the mean value (Mean) and the standard deviation (STD).

Table 4: Attenuation values upon penetration into the interior for glass (left) and a wall (right) for three different frequencies (Source[24])

Pol.	28 GHz		73 GHz		140 GHz	
	Mean (dB)	STD (dB)	Mean (dB)	STD (dB)	Mean (dB)	STD (dB)
V-V	1.53	0.60	7.17	0.17	10.22	0.22
V-H	20.63	1.32	37.65	0.53	46.92	2.05
H-V	22.25	0.88	36.92	1.11	37.37	1.79
H-H	1.48	0.54	7.15	0.44	10.43	0.55

Pol.	28 GHz		73 GHz		140 GHz	
	Mean (dB)	STD (dB)	Mean (dB)	STD (dB)	Mean (dB)	STD (dB)
V-V	4.15	0.59	2.57	0.61	8.46	1.22
V-H	25.59	2.85	24.97	0.58	27.28	1.77
H-V	25.81	0.65	23.38	0.65	26.00	1.42
H-H	3.31	1.13	3.17	0.68	9.31	0.61

The experiments confirm the theoretical assumptions; therefore, it cannot be expected that bands above 100 MHz will be used for combined outdoor and indoor coverage. Coverage will either be provided for clearly defined outdoor areas (e.g. town squares) or for indoor spaces via internal base stations (access points), in a similar way to how indoor spaces are covered by Wi-Fi networks.

The propagation characteristics of electromagnetic waves in the region close to 1 THz, which are superior to those of waves in lower regions of the spectrum, create the conditions for detecting the position of objects with an expected accuracy of centimetres, even in non-line-of-sight (NLOS) environments. However, there is still a long way to go before this can be put into practical use. However, the forthcoming 6G specifications are already taking this application area very seriously
with this area of application and highlight it as a significant added value.

[23] Minoru Inomata; Wataru Yamada; Nobuaki Kuno; Motoharu Sasaki; Koshiro Kitao; Mitsuki Nakamura; Hironori Ishikawa; Yasuhiro Oda – Scattering Effect up to 100 GHz Band for 6G. 2020 International Symposium on Antennas and Propagation (ISAP). https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=9391482

[24] T. S. Rappaport et al., "Wireless Communications and Applications Above 100 GHz: Opportunities and Challenges for 6G and Beyond," in IEEE Access, vol. 7, pp. 78729–78757, 2019, doi: 10.1109/ACCESS.2019.2921522

3.2.3 Antennas for the band above 100 GHz and their impact on link performance

An increase in the carrier frequency leads to a corresponding reduction in wavelength and, consequently, to smaller dimensions of the antenna elements. For reference, Table 5 shows the gradual reduction in wavelength as frequency increases.

Table 5: Examples of signal wavelengths at selected frequencies

Frequency in GHz	Wavelength
80	3.75 mm
140	2.1 mm
220	1.3 mm

Both the size of the antenna itself and the distances between individual elements will be reduced, making it possible to design multi-antenna architectures
with a very large number of antennas in a single antenna array (with high element density), thereby achieving spatial diversity for massive MIMO and favourable conditions for effective electronic beamforming (achieving high antenna gains in the desired direction
and minimising interference in other directions).

In the bands under consideration, the following types of antennas can be expected to be used:

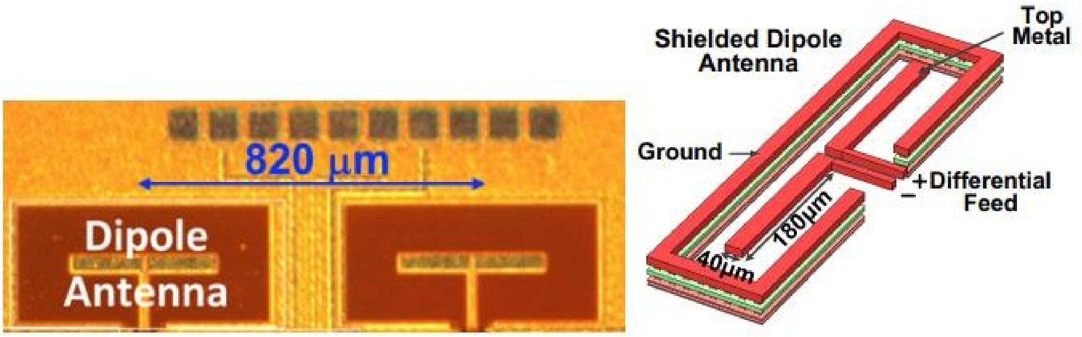
- Horn antennas
- Parabolic antennas
- Patch antennas
- SIW (Surface Integrated Waveguide) antennas

Horn antennas will be suitable for test measurements and point-to-point links. The same applies to parabolic antennas, where their high gain comes at the expense of beamwidth (the higher the gain, the narrower the beamwidth). Parabolic antennas are therefore also suitable for point-to-point links.

For commercial 6G deployment, planar-type antennas or antenna arrays (patch antennas) appear to be the most suitable. To increase gain, individual antennas can be grouped into antenna arrays or fields. This geometry ensures a narrow directional beam and thus high antenna gain. At the same time, 6G networks are expected to utilise beamforming, just as in 5G networks. This builds upon phased antenna arrays, where the parameters of the antenna beam or beams can be dynamically adjusted according to network requirements to ensure optimal connectivity.

Planar structure fabrication technologies are also suitable for the mass production of antennas (e.g. etching technology). Planar antennas, or SIW antennas, are integrated directly into Si chips, thereby enabling the implementation of a basic RF TX/RX module for an antenna array designed for beamforming. With these types of antennas, the gain and directional characteristics can be optimised to ensure optimal coverage of the target area (e.g. office spaces).

Figure 9: Example of part of an on-chip antenna array with miniature dipoles for the 210 GHz band[25]



The figure shows, for illustrative purposes, a photograph of an array of pairs of shielded dipole antennas on a chip, manufactured using 32 nm CMOS SOI technology. It is designed for a target frequency of 210 GHz. The distance between the antennas is only 820 µm and each dipole arm is only 180 µm long.

In such cases, given the wavelengths involved, it is necessary to take into account both the dimensions and the intrinsic geometry of the device (transmitter/receiver) – typically, in a mobile terminal, the arrangement of components around the antenna will significantly influence the transmission characteristics (absorption, reflections, scattering). Much more research and experimental work is still required in this area.

The type (design) of antennas for use in the 6G range (sub-THz band) will be determined by the requirements of the specific application (including ensuring a sufficient power level at the receiving end). Individual designs will vary according to the area of application (e.g. IoT, short-range communications, on-body communications, wireless APs, etc.).

With reference to the parameters affecting the power balance of a radio link, it can be stated that the range of such a radio link at a given frequency can be influenced by the transmit power and the gain of both the transmit and receive antennas. If, in addition to the parameters affecting the power balance, we also take legislative restrictions into account, it can be assumed that, within the conditions of a given band, the EIRP (equivalent isotropic radiated power) – which is the product of the transmit power and the gain of the transmit antenna – will be regulated. It follows that increasing antenna gain to compensate for high environmental attenuation has its limits and cannot be relied upon unconditionally.

3.3 The potential impact of wireless communication in bands above 100 GHz on the human body

The bands under consideration in the 100 to 300 GHz range for 6G networks belong to the same category of non-ionising radiation as the bands previously assessed at the advent of 5G. We refer here to information from the NRL.[26]

It is clear that 6G technologies will gradually be deployed in the lower bands used by today's mobile systems, including the 26 GHz band. The effects on the human body in these bands will not differ from those of the currently operating 4G and 5G systems, as the basic transmission principles and transmission power limits are identical.

The primary effect of exposure in the planned frequency band for sixth-generation networks, as with previous generations and other bands used by mobile networks, is tissue heating. Given the high frequencies and the shallow penetration depth of the waves into the tissue, the primary heating effect occurs on the body's surface; however, due to the high blood supply to the skin, volumetric heating may also occur. The resulting heating is, biochemically speaking, the main risk factor associated with exposure[27] ; however, it also serves as a useful dosimetric factor (indicating any increased radiation intensity), as exposure without heating is not possible. Exposure can therefore be limited by the maximum permissible heating of the skin, which, for typical exposure scenarios, is directly proportional to the areal energy density

---

[25] Z. Wang et al., "A CMOS 210-GHz fundamental transceiver with OOK modulation," IEEE J. Solid-State Circuits, vol. 49, no. 3, pp. 564–580, Mar. 2014.

[26] Information No. 20/2019 from the National Reference Laboratory (NRL) for Non-ionising Electromagnetic Fields and Radiation – Risks of human exposure to electromagnetic fields in fifth-generation telecommunications networks

[27] Guidelines for limiting exposure to electromagnetic fields (100 kHz to 300 GHz). Health Physics 118(5):483–524; 2020.

incident on the body surface. For exposure lasting at least several minutes, a radiant flux density of 10 W/m^2[28] may be considered a conservative exposure limit, i.e. the value also used within the frequency bands of fourth- and fifth-generation networks.

A distinctive feature of sixth-generation networks is the use of higher frequencies. Given the high free-space losses, it can therefore be assumed that, compared with previous-generation networks and lower frequency bands, the use of highly directional beams will be necessary. If we choose a Gaussian beam as the general physical model, the radiant flux density (a dosimetric quantity) at the centre of the radiating aperture (worst-case exposure scenario)$S_0 \sim D^2 / A^2$ directly proportional to the square of the distance D between the transmitter and the receiver and inversely proportional to the square of the area A of the transmitting aperture. Since, in conventional systems using a directional beam, the area A will be proportional to the square of the wavelength regardless of frequency, it follows that, given the same bit rate, the same bandwidth and the same receiver design, the radiant flux density will be inversely proportional to the fourth power of the wavelength.

The inverse proportionality of maximum exposure to the fourth power of the wavelength may mean that directional beam antenna systems, which are considered to be of no health significance in fourth- and fifth-generation networks, may become exposure-relevant at the higher frequencies envisaged for sixth-generation networks, should an exposed person be permitted to be in the vicinity of the aperture.

However, the impacts of the bands under consideration and the use of narrow directional beams are, and will continue to be, the subject of intensive research in the coming period, in line with the development of views on the use of bands above 100 GHz and the ongoing standardisation process. This will also include adaptive systems for targeted beam steering, utilising propagation paths with minimal losses, which will ultimately ensure that power is concentrated away from the human body, resulting in high signal attenuation. A large proportion of applications, particularly for indoor coverage, will also operate at low radiated power levels; it can therefore be assumed that exposure will be safely below the health limits currently recognised.

It is clear that careful studies must be carried out to analyse the effects of radiation in the THz range on living organisms. At the same time, the question arises as to whether such radiation could, in some cases, be used as a safer and sufficiently effective alternative to methods utilising ionising radiation, such as X-rays and CT/PET scans[29] .

---

[28] Guidelines for limiting exposure to electromagnetic fields (100 kHz to 300 GHz). Health Physics 118(5):483–524; 2020.

[29] T. S. Rappaport et al., "Wireless Communications and Applications Above 100 GHz: Opportunities and Challenges for 6G and Beyond," in IEEE Access, vol. 7, pp. 78729–78757, 2019, doi: 10.1109/ACCESS.2019.2921522

4 Prospects for the use of the band above 100 GHz, an analysis of regulatory and standardisation aspects

4.1 Summary of the physical principles and expected characteristics

4.1.1 Properties of the band

Frequency bands above 100 GHz, capped at 1 THz (sub-THz bands, although practical use is currently anticipated up to approximately 300 GHz), belong to the group of millimetre- to sub-millimetre-wave bands, which, according to the latest research findings, can be utilised for transmission at ultra-high data rates. This band has been identified as one of the bands for the development of 6G mobile networks after 2030.

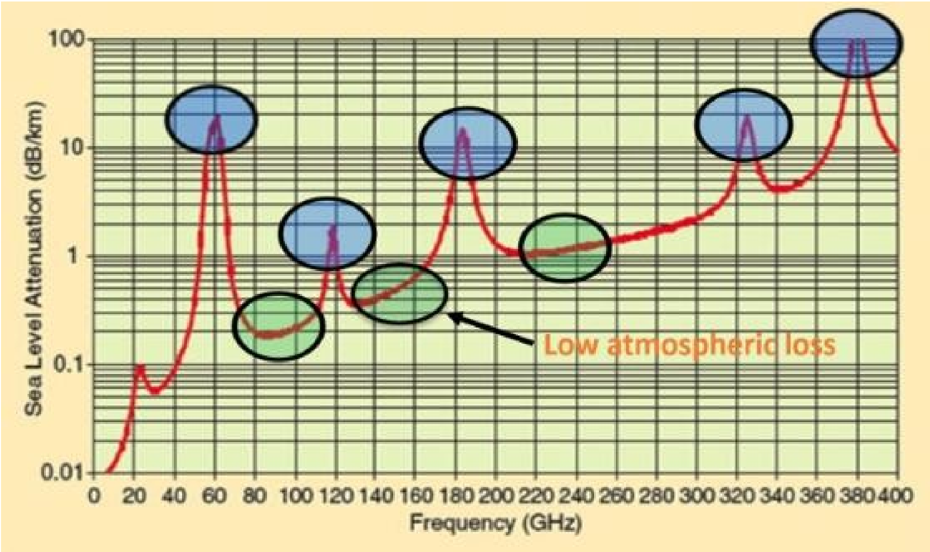
Millimetre-wave frequency bands are typically characterised by a very limited range due to the predominant nature of line-of-sight propagation and high environmental attenuation. This fact, combined with the expected small size of antenna arrays (due to short wavelengths), will lead to their use primarily for covering interiors and relatively small, confined areas (stadiums, squares, etc.). The expansion of the use of the band above 100 GHz can be achieved using Reconfigurable Intelligent Surfaces (RIS), which enable controlled coverage even of small areas outside the line of sight. This appears suitable, for example, in industry.

Different frequency bands are subject to varying degrees of atmospheric absorption (e.g. absorption by oxygen and water molecules), resulting in additional signal level losses during free-space propagation. In addition to the current use of the spectrum for short-range applications in the 60 GHz band, the
as well as the 120, 183, 325 and 380 GHz bands (blue circles in the graph). The graph also shows the 77, 140 and 240 GHz bands (green circles), which exhibit only 1 dB/km or less of loss compared to free-space attenuation and are suitable for long-range broadband mobile devices and fixed-point applications.

Channels above 92 GHz are characterised by short wavelengths, high bandwidth and a narrow radiation beam. The channel will therefore be sensitive to changes in the time, frequency and spatial domains, and can be expected to be non-stationary, meaning that its parameters will vary considerably over time. Furthermore, this non-stationarity may manifest itself in different ways in different scenarios, which will place high demands on the adaptive methods implemented in the receiver and transmitter, and on the management of access to radio resources.[30]

[30] ITU-R Report M.2541-0 (05/2024): Technical feasibility of IMT in bands above 100 GHz

Figure 10: Graph showing attenuation peaks (blue) caused by atmospheric absorption and windows (green)[31]



Summary of the characteristics of sub-THz bands:

- High free-space attenuation – attenuation due to oxygen and water molecules
- The 80 GHz, 140 GHz and 220 GHz bands appear to be the most suitable for communications
- Suitable for short-range communications, typically ranging from a few metres to the lower tens of metres; under certain conditions, ranges can extend to hundreds of metres (antenna arrays) or up to a few kilometres (e.g. when using parabolic antennas)
- Suitable for indoor applications where there are no dynamic changes in the microclimate (humidity)
- Low penetration through materials – scattering occurs at the air/material interface
- High wave scattering effect on the material (material roughness) – scattering increases with rising frequency – this negative effect is utilised in the field of communications, for example in material diagnostics

4.1.2 Fulfilment of expected characteristics

According to the IMT-2030 specification, which sets out the ITU-T's vision for network development towards 2030, certain key characteristics are expected of 6G networks. The following table summarises how bands above 100 GHz will enable these characteristics to be met.

Table 6: Fulfilment of expected 6G network characteristics according to IMT-2030, with the potential use of bands above GHz

Key characteristics	Expectations for 6G	Relationship to bands above 100 GHz
Maximum data transmission rate	50, 100, 200 Gbit/s	These speeds are realistically achievable with bandwidths of 1 GHz and above, which is only possible in the frequency range above 100 GHz.
Commonly available transmission speeds	min. 300/500 Mbit/s	These speeds can also be achieved in lower parts of the spectrum, but this depends on the number of terminals communicating simultaneously.
Connection density	up to 100 million devices per km^2	Device density is directly related to the bandwidth, but also depends on many other factors.

[31] Y. Xing and T. S. Rappaport, "Propagation Measurement System and Approach at 140 GHz—Moving to 6G and Above 100 GHz," 2018 IEEE Global Communications Conference (GLOBECOM), Abu Dhabi, United Arab Emirates, 2018, pp. 1–6, doi: 10.1109/GLOCOM.2018.8647921. https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8647921

Delay between end devices	0.1–1 ms	Latency is not directly related to transmission speed or bandwidth. It depends on the length of the data communication frame and the data exchange procedures between the base station and the terminal.
Traffic density	30/50 Mbit/s per 1 m^2	This traffic density is realistically achievable with bandwidths of 1 GHz and above, which is only possible in the frequency range above 100 GHz.
Mobility	500–1,000 km/h	This is not directly related to spectrum bandwidth, but rather to the optimisation of the radio layer and the communication protocol.
Positioning accuracy	1–10 cm	Positioning accuracy approaching 1 cm is possible only in the extremely short-wave range, i.e. at frequencies above 100 GHz.

4.1.3 Application areas

In accordance with ITU-R Recommendation M.2160-0 (11/2023), three core and three enabling application areas are defined, which are expected to be realised in the context of bands above 100 GHz, as shown in the table below.

Table 7: Fulfilment of expected 6G network application areas according to IMT-2030, with the possible use of bands above GHz

Areas of application	Expected applications	Coverage of requirements by bands above 100 GHz	Note:
Advanced high-speed mobile networks	8K video, 360° video, XR, multimodal communication, etc.	Transmission capacity with ample headroom for high terminal density.	Achievable even in lower frequency bands.
Highly reliable, low-latency communication	Industry, transport, energy.	Not directly related to these bands.	We anticipate use primarily in indoor environments (production halls, etc.).
Massive communication between devices	Internet of Things, sensors, smart cities and buildings.	Use of these bands is not anticipated.	Rather, this involves small volumes of data between devices at high density.
Ubiquitous communication	Full coverage of both outdoor areas and interiors. Communication between robots and AI components.	This may involve significant volumes of data, where a wide bandwidth is an advantage.	
Integrated detection and positioning	Position tracking and object detection.	Extremely short wavelengths are required for accuracies of 1 cm or less.	
AI and communication	Data exchange for training, use of AI to optimise the network.	This may involve significant volumes of data, where wide bandwidth is an advantage.	

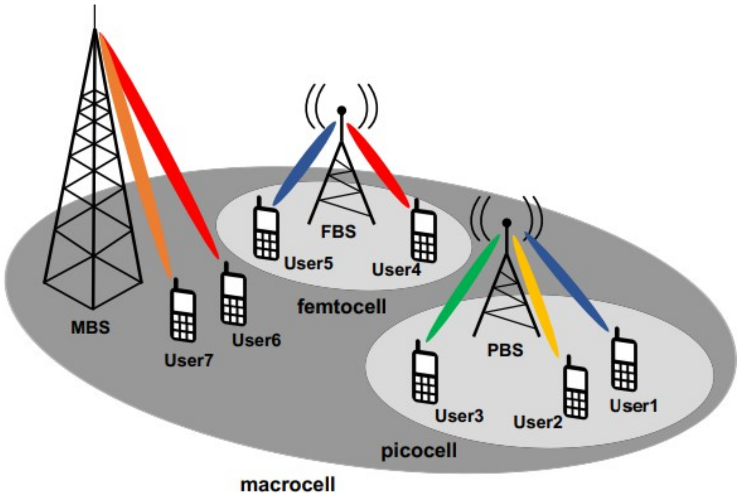
4.2 Use cases and licensing options for new bands for 6G networks

4.2.1 Radio access network

In line with the need for high-speed connectivity, infrastructure can be implemented using base stations with a large number of antennas (>100) and beamforming, providing high-speed wireless access for users spread across a wide area by utilising multiple spatial channels simultaneously from different base stations. To a certain extent, this
reduces the need for extremely wide frequency bands, as existing bands are shared very efficiently by a large number of parallel communication links (spatial multiplexing) and the 26 GHz band can be utilised to saturation for a relatively long period.

In line with the trend towards the use of higher frequency bands, selected areas will see increased signal density from base stations covering a locally limited area (femto-cell, pico-cells), whilst wide-area coverage will continue to be provided, as before, by base stations operating in standard (lower and mid-range) frequency bands (macro-cells), as illustrated in the following figure.

Figure 11: Illustration of global coverage using large cells (macro-cells) and local connectivity supplementation via extremely small cells (femto-cells, pico-cells)[32]



In general, 6G networks will utilise both existing mobile network bands and new ones. After 2030, it can be assumed that the original GSM voice communication bands will already be in use for current 5G/6G networks. For a sufficiently long period, compatibility between 5G networks and the emerging 6G networks will then be ensured across a given set of bands, which will be utilised according to the nature of the area, the terrain, the expected density of terminals, the volume of traffic and the mix of services used.

The following table shows the potential of bands above 100 GHz in relation to the size and nature of the area covered.

[32] P. Heydari. Transceivers for 6G Wireless Communications: Challenges and Design Solutions. IEEE CICC 2021/ Session 12: mm-Wave Circuits and Transceivers/ Paper 12-1.

Table 8: Usability of bands above 100 GHz in relation to the size and nature of the coverage area and the service

Areas of application	Potential of bands above 100 GHz	Note:
Wide-area coverage – large cells	Not applicable	Short range, poor penetration into buildings
Coverage of linear infrastructure (motorways, railway corridors)	Not an option; only limited sections of linear infrastructure, such as railway stations, border crossings, toll gates, etc.	Low range, poor penetration into buildings. However, bands above 100 GHz are suitable for direct vehicle-to-vehicle (V2V) communication.
Coverage of limited open spaces (squares, parks, playgrounds)	Suitable for use once the potential of the 26 GHz bands or other bands below 100 GHz has been exhausted.	
Coverage of large indoor spaces (halls, conference centres and shopping centres)	Suitable for use once the potential of the 26 GHz band or other bands below 100 GHz has been exhausted.	
Coverage of indoor spaces (offices, residential premises)	Suitable for use once the potential of the 26 GHz band or other bands below 100 GHz has been exhausted.	Use of the femto- and pico-cell concept
Coverage of production and warehouse halls via private industrial networks	Suitable for use once the potential of the 26 GHz band or other bands below 100 GHz has been exhausted.	Suitable combination of communication and position detection
Direct device-to-device (D2D) communication	Suitable for direct communication over short distances of up to tens of metres.	

Examples of use and possible scenarios are also covered in ITU-R Report [33]. The following options are considered in particular:

- **An indoor hotspot** in a large meeting room or **an outdoor hotspot**. Small base stations can meet the needs of applications requiring extremely high data rates, such as holographic displays, etc. Spaces such as large meeting rooms represent relatively enclosed environments. Given the high attenuation in bands above 92 GHz, high-gain directional antennas or large antenna arrays can be used to flexibly establish wireless connections to outdoor base stations; these can provide higher gains and improve the attenuation balance. Deployment of base stations
  Higher density can provide users with better coverage, but it also brings problems with interference; however, this will not be as critical in these high parts of the spectrum, where there is greater path loss and lower penetration through obstacles.
- **High-speed short-range links**. High-speed point-to-point (peer-to-peer) links can also utilise the key characteristics of radio bands in the higher regions of the spectrum. Direct device-to-device communication and mesh network functionality can be put to good use here. This reduces the load on the base station's data traffic and also minimises latency between mobile devices. Device-to-device (D2D) and vehicle-to-vehicle (V2V) communication are two representative types of this kind of connection, already familiar from 5G networks. Internal direct device-to-device (D2D) communication also envisages the deployment of low-cost devices with lower transmission power and antennas that are much smaller compared to standard equipment. The distance between communicating devices is likely to be less than 5 m.
- **Private industrial networks**, typically covering halls, production areas and adjacent spaces, can benefit both from high data rates and from the ability to detect objects and track their precise locations.

[33] ITU-R Report M.2541-0 (05/2024): Technical feasibility of IMT in bands above 100 GHz

- **Transport applications**. High-speed adaptive links between antennas on train roofs and the infrastructure can be used to transmit both safety information and aggregated passenger data. Inside the vehicles, a moving hotspot can then be created for passengers.

However, it must be borne in mind that at extreme transmission speeds, the range will be very limited. For example, the achievable communication distances at a speed of 100 Gbit/s, with line-of-sight conditions at a frequency of 300 GHz and a bandwidth of 30 GHz, will be only 18 to 30, metres, depending on the type of terrain.

4.2.2 Use of the band above 100 GHz for access networks

Sixth-generation wireless networks will offer significantly higher capacity at the radio interface, which will also translate into a need for ultra-high-capacity access networks (so-called mobile **backhaul**). Not all base stations can be connected via optical fibre, although the proportion of those that can is increasing. Where radio relay links remain necessary, bands in the 80 GHz or, in some cases, 60 GHz range are currently used. However, these are limited to operational speeds of approximately 10 Gbit/s. Higher available capacities at this network level may, in the future, be achieved by utilising as yet unused parts of the spectrum above 100 GHz, with channel bandwidths in the range of tens of GHz. It is expected that transmission capacity comparable to that of optical fibres will be provided for the purposes under consideration. This solution is suitable for scenarios or environments where optical fibres cannot be deployed or where their deployment is difficult. Access nodes may take the form of traditional fixed base stations or may be flexibly deployed or mobile (airborne) base stations.

However, current spectrum management conditions as yet prevent the allocation of sufficiently wide and contiguous bands for communication at these frequencies, as several relatively narrow bands are reserved to protect passive monitoring services.
These include radio astronomy and Earth observation by satellites using sensors that may be interfered with by active transmitters. Methods are being investigated and experiments conducted which demonstrate that spectrum sharing above 100 GHz between active and passive services is feasible, for example through the introduction of adaptive communication systems that monitor the presence of passive users in real time and prevent interference by automatically switching to bands outside the area currently being monitored.[34]

4.2.3 Use of the band above 100 GHz for local and personal networks

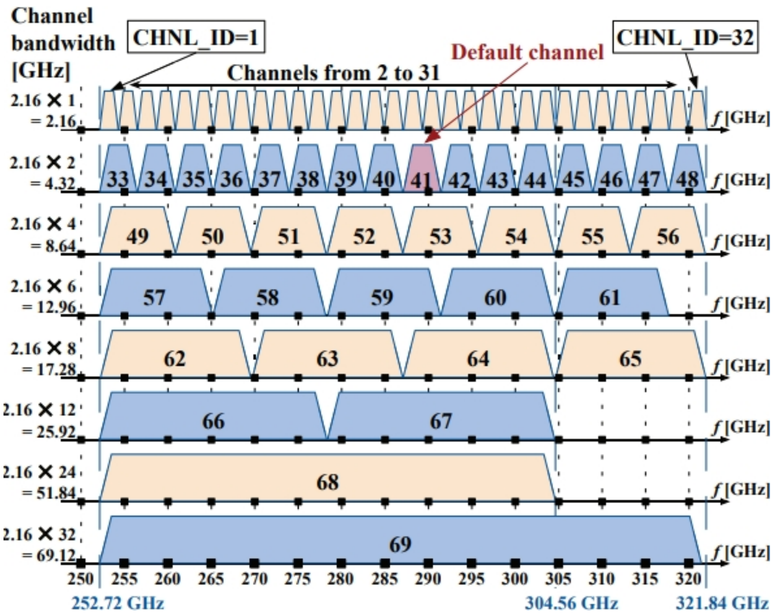
Alongside mobile networks based on 3GPP specifications, wireless communication based on IEEE standards is also being developed. Specifically, we shall mention the IEEE 802.15.3d standard for local and personal networks (Wireless Personal Area Networks – WPAN).

Devices compliant with the IEEE 802.15.3d specification are intended to operate at sub-THz frequencies between 252.72 GHz and 321.84 GHz. There are a total of 69 overlapping channels. Eight supported bandwidths are available, with channel widths starting from 2.16 GHz, as shown in the diagram below.

---

[34] Michele Polese, Viduneth Ariyarathna, Priyangshu Sen, Jose V. Siles, Francesco Restuccia, Tommaso Melodia, Josep M. Jornet: Dynamic spectrum sharing between active and passive users above 100 GHz. COMMUNICATIONS ENGINEERING, 2022, https://doi.org/10.1038/s44172-022-00002-x

Figure 12: Illustration of bands and channelisation for WPAN networks[35]



Although a standard is in place and there is a clear vision for the use of this band, practical applications are still pending. In particular, work is underway on the development of transmitting and receiving equipment with the required characteristics, as well as antenna elements; it will take some time before we reach the commercial stage of utilisation.

4.2.4 International spectrum coordination for mobile networks

International spectrum coordination at a global level takes place at regular four-year intervals as part of the World Radiocommunication Conferences, the most recent of which was held in 2023 (WRC-23). We provide here a summary of those WRC-23 resolutions relating to spectrum for international mobile communications.

Resolution No. 255[36]is key for bands above 100 GHz. This is followed by Resolution No. 721, which concerns the adjacent 275–325 GHz frequency band. According to these resolutions, which specifically cover bands above 100 GHz, all preparatory work, feasibility studies, service coexistence analyses, etc., should be completed in time for the World Radiocommunication Conference in 2031, which will be crucial for their commercial opening.

Resolution No. 256[37]concerns further bands for mobile communications situated in lower frequency ranges. Under this resolution, the ITU Radiocommunication Sector has called for the completion of documentation specifying bands in the lower regions of the spectrum for terrestrial IMT networks, so that final conclusions can be adopted at the World Radiocommunication Conference in 2027. The frequency bands under consideration are as follows:

- 4 400–4 800 MHz or parts thereof in Region 1 (including Europe) and Region 3
- 7,125–8,400 MHz or parts thereof in Region 2 and Region 3
- 7,125–7,250 MHz and 7,750–8,400 MHz or parts thereof in Region 1 (including Europe)
- 14.8–15.35 GHz

However, at the World Radiocommunication Conference (WRC-23), Europe did not actively propose the study of further IMT bands listed in ITU-R Resolution No. 256. The study item is therefore the result of a compromise that took into account the requirements of other regions

[35] IEEE 802.15.3d

[36] RESOLUTION 255 (WRC-23): Studies on frequency-related matters for the identification of International Mobile Telecommunications (IMT) in the frequency bands [102–109.5 GHz, 151.5–164 GHz, 167–174.8 GHz, 209–226 GHz and 252–275 GHz] for the future development of IMT

[37] RESOLUTION 256 (WRC-23): Sharing and compatibility studies and the development of technical conditions for the use of International Mobile Telecommunications (IMT) in the frequency bands 4 400–4 800 MHz, 7 125–8 400 MHz (or parts thereof), and 14.8–15.35 GHz for the terrestrial component of IMT

and ITU consultation procedures, taking into account the principles of consensus. Consequently, the conclusions of the CEPT (European Conference of Postal and Telecommunications Administrations) expert groups and the position of the European Union will be particularly relevant for conditions in Europe.

The current status and position regarding these bands within the CEPT is as follows:

- The task of examining the options for IMT in the specified bands has been entrusted to the relevant working groups. Initial discussions on these bands have not yet yielded more stable preliminary options for discussion; however, the starting point is Europe's position at WRC-23, which did not recommend these bands for IMT due to the operation of a number of critical applications and systems, such as NATO communications and satellite communications in Europe.
- The 4 400–4 800 MHz band is used intensively by aviation and maritime systems within CEPT and worldwide on a continuous 24/7 basis to support national security and humanitarian aid. Furthermore, it is necessary to ensure coexistence with radio altimeter systems in the 4,200–4,400 MHz band and other systems in that band.
- The 7 125–8 400 MHz band is used extensively by satellite services (downlink 7.25–7.75 GHz, uplink 7.9–8.4 GHz) and terrestrial systems on a continuous 24/7 basis to support national security and for humanitarian aid. It is also used for temporary point-to-point (PTP) video links in the 7–8.5 GHz frequency range, specifically for portable and mobile stations.
- The 14.8–15.35 GHz band is used by the aeronautical mobile service and the fixed service for government applications within CEPT territories and at international level worldwide, operating continuously 24/7 to support national security and for humanitarian aid. Various space agencies operate communications in this band for current and future missions, including manned missions.

4.2.5 Assessment of spectrum usage for 5G and analysis of further requirements for 6G in Europe

The RSPG carried out an assessment of the 5G roll-out process in Europe (frequency licensing strategies, auction procedures, deployment processes, etc.) with the aim of gaining insights into what has been successful and what still needs to be addressed, in order to inform the design of strategies for the next generation of mobile networks, 6G.[38]

In order to make the necessary new allocations of harmonised spectrum for 6G available in good time, it is essential to support research and feasibility studies in the 100 GHz to 1 THz bands.

The RSPG notes that the roll-out of 5G is taking place primarily in the primary bands designated for 5G:

A. The 700 MHz band was harmonised across the EU as early as 2016. It was originally planned and used in some countries for 4G and has now begun to be used for 5G. The band provides good coverage but, due to its low bandwidth, offers lower data rates.
B. The 3.6 GHz band is the primary band for the roll-out of 5G networks in Europe, with a harmonised spectrum of 400 MHz.
C. The 26 GHz band is utilised quite differently across individual EU Member States. The roll-out of 5G has been slow even in those Member States that have made this band available to the market. The so-called millimetre-wave (mmW) band can meet the demand for very high capacity in densely populated areas and offers potential for new types of networks, services and business models. However, this band does not provide widespread coverage due to the different signal propagation characteristics compared with other bands, and it requires significant investment in networks, which may not yet always be deemed to offer a sufficiently rapid return on investment.

The testing phase in the 26 GHz band is still ongoing; commercial use has already begun in some countries and is expected to increase as the availability of equipment improves in the coming years and mobile network operators become willing to densify their networks (e.g. in response to user demand for fixed wireless access solutions).

With the advent of 5G, new solutions have been introduced for more dynamic and shared use of the spectrum. This need is expected to grow with the development of 5G and the roll-out of 6G.

- Dynamic in-network spectrum sharing enables radio resources to be shared on demand in real time between 4G and 5G technologies (with 6G also expected to be included in the future). This provides an opportunity to rapidly roll out new technologies to customers without the need to phase out older technologies.
- Some Member States have also introduced models for the leasing of spectrum (particularly in the 3.6 GHz band) by mobile network operators to third parties (e.g. industrial enterprises for private 5G) and models for spectrum sharing between mobile network operators (particularly in the 26 GHz band).

[38] RSPG23-026 FINAL RADIO SPECTRUM POLICY GROUP: The development of 6G and possible implications for spectrum needs and guidance on the rollout of future wireless broadband networks. Brussels, 14 June 2023

- Mechanisms for dynamic spectrum sharing between different terrestrial mobile networks and other types of networks are emerging, e.g. for emergencies and other temporary needs, and could be further developed on a larger scale for 6G as well.

Growing demand for spectrum used in vertical and local applications.

- Some Member States have already allocated spectrum for local and vertical applications, and the spectrum requirements for these continue to grow.
  Current national implementations include dedicated spectrum, for example in the 400 MHz and 2.3 GHz bands and in the harmonised 2.6 GHz, 3.6 GHz and 26 GHz bands.
- In some Member States, voluntary harmonisation in the 410–430 and 450–470 MHz bands responds to user requirements, particularly from public services.
- In addition, the Commission has issued a mandate to the CEPT ‘on technical conditions relating to the shared use of the 3.8–4.2 GHz frequency band for terrestrial wireless broadband systems providing local network connectivity in the Union’. Alongside national initiatives, work will continue on defining harmonised technical conditions (with harmonisation expected in 2025) for low- and medium-power terrestrial wireless broadband (WBB LMP, intended for use in local and campus networks).
- The 42 GHz band will be a possible extension above the 26 GHz band as part of the second stage of mmW bands. The 42 GHz and 26 GHz bands, as recommended in RSPG Opinion 21-024, may enable local spectrum use. This band is the subject of a separate study[39]

As technology neutrality applies, the existing harmonised bands, currently used for GSM, LTE and 5G, will be made available and utilised for 6G as well.

The RSPG further highlights the need for licence-exempt or limited-licence spectrum to support certain aspects of 6G operations and the provision of private and personal networks. This spectrum will facilitate connectivity for end-users, machine-to-machine communication and the deployment of other applications that do not require predictable quality of service.

Non-terrestrial radio networks could become an important complementary layer of connectivity to terrestrial connectivity services, for example by providing coverage in underserved areas, delivering global connectivity for logistics and transport, supporting disaster relief, and serving as a backup layer or backhaul for terrestrial networks.

A proactive approach is essential to support the development and roll-out of 6G. This includes further work by the RSPG to identify spectrum requirements at an early stage, so that the roll-out of 6G networks can begin after 2030.

The RSPG’s 6G Vision Working Group is discussing, amongst other things, operational and user models for 6G. The range of issues the group is addressing in depth includes, for example, the following:

- Private 5G/6G applications and networks (in dedicated spectrum bands, in public spectrum bands and supported by public mobile networks).
- The roll-out of 6G networks – coordinated timing of roll-out across the EU, support for the single market, and the role of spectrum sharing, including dynamic sharing.
- Possibilities for utilising licence-exempt parts of the spectrum.
- The use of non-terrestrial networks (the role of NTNs, UAV base stations, satellites) and the implications for spectrum management.
- Sustainability and security.

4.2.6 Options for licensing bands above 100 GHz

Given their propagation characteristics and practical applicability, bands above 100 GHz will be most similar to the 26 GHz band, currently allocated to 5G networks. Although this band is not yet in commercial use in the Czech Republic, some practical experience has already been gained from experimental operations, and there is a relatively clear picture of the options for its use and licensing. This issue is analysed in detail in a separate study[40]. The most important facts can be summarised as follows:

- In the Czech Republic, according to the Radio Spectrum Utilisation Plan No. PV-P/2/10.2020-10, the 26.5–27.5 GHz band is designated for the provision of wireless broadband electronic communications services. Five adjacent 200 MHz blocks with time-division duplex (TDD) are defined within this band. The use of these frequencies is currently envisaged on the basis of individual authorisations for the use of radio frequencies (at present permitted only for experimental purposes).

[39] Analysis of current and future use of the 42 GHz band, GTA study for the Ministry of Industry and Trade. 2024.

[40] Analysis and proposal for the use and allocation of frequencies in the 26 GHz band, GTA, MPO, 2024.

- The band offers particular potential for the so-called vertical sector. In terms of the frequency bands in use, the following options can be identified:
  - Where the use of the radio spectrum requires an individual licence, the granting of frequencies ensures that the user has direct control over the allocated frequencies.
  - An alternative solution is to obtain the right to use frequencies by leasing them from an entity that holds the rights (e.g. a mobile operator). This approach is already permitted in the Czech Republic in other 4G/5G bands and is also used in a number of other European countries.
  - Another option is to use frequency bands under a general authorisation. An example is the operation of a campus or industrial network within a building or enclosed premises, where there is a low likelihood of interference from other users.
  - Another approach is the provision of a ‘turnkey’ solution by an electronic communications network or service operator. The solution provided may take the form of wholesale access, roaming, a virtual private network, or network slicing.
- Four potential models for securing wireless connectivity for the vertical sector can be identified, which differ in their varying degrees of separation from public networks:
  - The highest degree of separation is the construction and operation of a private network.
  - Approaches based on the use of public network elements and access to the relevant frequency band at wholesale level can be divided into three groups:
    - sharing of public access network (RAN – Radio Access Network) infrastructure, possibly via RAN slicing where available, or via MORAN (Multi-Operator RAN) or MOCN (Multi-Operator Core Network).
    - Sharing of both the RAN and the network core
    - full provision of the service by the operator, with the vertical entity’s role limited to managing the application layer.

The CTU anticipates three use cases for the 26 GHz band:

- Fixed Wireless Access (FWA) – initial primary use
- 5G in outdoor environments (potentially MNOs, but more likely campus networks)
- 5G in indoor environments (campus networks, possibly in combination with outdoor coverage).

Once the 26 GHz band, or any other internationally coordinated bands under consideration for mobile communications, have been utilised and fully exploited, it will become clear whether demand is growing to such an extent that it is necessary to proceed with the commercial use of bands above 100 GHz. It can be assumed that this will not happen in the Czech Republic before between 2035 and 2040.

Possible basic licensing regimes for bands above 100 GHz:

- For applications with low radiated power and advanced active antenna systems, it can be tentatively assumed that the operating conditions (such as radiated power or spectral power density, channel bandwidth, etc.) will allow licence-exempt operation (i.e. under a general authorisation) for many 6G applications.
- For specific applications with higher radiated power, or more generally in situations where radio spectrum sharing and the associated risk of mutual interference between stations would not be acceptable to users, the possibility of granting individual authorisations is also likely to be discussed.

Following on from the scenarios discussed in the context of 26 GHz band licensing, we provide comments in tabular form on whether and how these could also be applied to bands above 100 GHz (excluding point-to-point links, which are of a specific nature due to their narrow signal beams).

Table 9: Relevance of radio resource allocation scenarios considered for the 26 GHz band in view of a future shift to bands above 100 GHz

Radio resource allocation scenarios under consideration for the 26 GHz band		Relevance for bands above 100 GHz
1.	Frequency allocation for a specific base station	This is possible but unlikely – a larger number of base stations will be required.
2.	Allocation of frequencies for a defined operational area covering multiple base stations	This will be one of the primary methods for covering outdoor areas
3.	Area-wide allocation of a specific frequency block	This is unlikely given the local nature of usage
4.	Allocation exclusively for indoor use	Likely method of use

Table 10: Relevance of the frequency licensing scenarios under consideration for the 26 GHz band in view of the future shift to bands above 100 GHz

Frequency licensing scenarios under consideration for the 26 GHz	Relevance for bands above 100 GHz
1. Allocation/availability of frequencies under a general authorisation	The basic option under consideration for low-power systems
2. Allocation/availability of frequencies on the basis of an individual licence following an application	Option for systems with higher radiated power for external applications
3. Allocation/availability of frequencies on the basis of a competitive tender	Option for systems with higher radiated power for external applications

Table 11: Relevance of frequency licensing scenarios in terms of geographical scope, as considered for the 26 GHz band in view of a future shift to bands above 100 GHz

Frequency licensing scenarios under consideration for the 26 GHz in terms of geographical scope	Relevance for bands above 100 GHz
1. Nationwide coverage	This will not be technically or economically feasible
2. Local option A – geographical demarcation based on administrative divisions (e.g. region, district, town, municipality)	A possible option for outdoor use, but only for small areas at municipal level
3. Local variant B – geographical scope determined by the technical parameters (coverage) of the network	Likely option for outdoor use, covering small-scale areas such as town squares and village centres

5 Conclusions and recommendations

Mobile networks are built on the basis of standards set by the 3GPP (3rd Generation Partnership Project), which are under continuous development. In reality, therefore, this is not a matter of revolutionary generational leaps, but a gradual process of innovation. In the near future, we can expect the completion of the 5G-Advanced specification, which will introduce a number of new features already hinting at the next generation, 6G. A fully-fledged 6G network is likely to be standardised by 2028 (Release 21), and practical deployment and use are in a number of countries, including in Europe, is expected around 2030. A more detailed description of the features and the transition process from 5G to 6G is set out in a separate chapter of this study.

Frequency bands above 100 GHz, with an upper limit of 1 THz (sub-THz bands, although practical use is currently anticipated up to approximately 300 GHz), belong to the group of millimetre-wave to sub-millimetre-wave frequencies, which, according to the latest research findings, can be utilised for transmission at ultra-high speeds. This band has been identified as one of the bands for the development of 6G mobile networks after 2030.

International spectrum coordination at a global level takes place at regular four-year intervals as part of the World Radiocommunication Conferences, the most recent of which was held in 2023 (WRC-23). Resolution No. 255 recommends designating the 102–109.5 GHz, 151.5–164 GHz, 167–174.8 GHz, 209–226 GHz and 252–275 GHz bands for mobile networks and services. This is followed by Resolution No. 721, which concerns the adjacent 275–325 GHz frequency band. According to these resolutions, all preparatory work, feasibility studies, service coexistence analyses, etc., should be completed in time for the 2031 World Radiocommunication Conference, which will be crucial for their commercial opening.

Frequency bands above 100 GHz are typically characterised by very limited range due to the predominant nature of line-of-sight propagation and high environmental attenuation. This fact, combined with the expected small size of antenna arrays (due to short wavelengths), will lead to their use primarily for covering indoor spaces and relatively small, confined areas (stadiums, squares, etc.).

However, based on the current state of knowledge, a dramatic increase in demand from 5G to 6G among ordinary users cannot be expected. LTE-Advanced (4G) technology is already sufficient for most of today's needs, and there is little incentive for ordinary users to switch from 4G to 5G. A similar situation is likely to recur during the transition from 5G to 6G, and market players will face a major challenge in convincing users of the benefits of 6G. In this context, expansion into bands above 100 GHz does not seem particularly pressing and is likely to be necessary only in the long term (after 2040). What is certain is that technological development continues, and there is a need to introduce new technologies, features and services. The question is what the real benefits and practical advantages are for people, setting aside technology enthusiasts and those who cannot do without the very latest models available on the market. Indeed, the focus of innovation will increasingly shift towards industry, transport, healthcare, agriculture, defence and machine-to-machine communication.

Once the 26 GHz band – and any other bands under consideration that are internationally coordinated for mobile communications – have been utilised and fully exploited, it will become clear whether demand is growing to such an extent that it is necessary to proceed with the commercial use of bands above 100 GHz. It can be assumed that this will not happen in the Czech Republic before between 2035 and 2040.

The possible basic licensing regimes for bands above 100 GHz are as follows:

- For applications with low radiated power and advanced active antenna systems, it can be tentatively assumed that the operating conditions (such as radiated power or spectral power density, channel bandwidth, etc.) will allow licence-exempt operation (i.e. under a general authorisation) for many 6G applications.
- For specific applications with higher radiated power, or more generally in situations where the sharing of the radio spectrum and the associated risk of mutual interference between stations would not be acceptable to users, the possibility of granting individual authorisations is also likely to be discussed.

A more detailed analysis of potential uses and licensing scenarios, in relation to the currently relevant 26 GHz band, is set out in the text of the study.

We recommend closely monitoring developments in this area and actively contributing to the discussion in international forums on the use and licensing of spectrum bands for 6G networks (ITU-R, WRC, RSPG, CEPT). To adopt positions and recommendations in a timely manner and formulate a strategy for the roll-out of 6G networks in the Czech Republic (the appropriate timeframe for formulating this strategy appears to be around 2025/26). To support education and the development of know-how in this field.

At the same time, we recommend monitoring the use of current spectrum bands, the evolution of customer requirements and the development of services, and, on this basis, updating the requirements for utilising spectrum bands above 100 GHz, particularly from the perspective of expected investments and their realistic return on investment.

We further recommend supporting research and further specialist studies in this area through appropriate grant schemes and funding mechanisms. In the initial phase (approximately 2025 to 2027), the focus should be on theoretical and experimental work carried out by the academic sector and research organisations. In the subsequent phase (approximately 2028 to 2030+), the focus should shift to applied research and collaboration between research organisations and industrial enterprises on specific use cases, and the development and testing of specific products and solutions. To this end, it will be necessary to make the relevant parts of the spectrum available for experimental use well in advance.

UNOFFICIAL MACHINE TRANSLATION

www.grantthornton.cz