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Future technology trends of terrestrial International Mobile Telecommunications systems towards 2030 and beyond

M Series

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(2022)

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1 Introduction

International Mobile Telecommunications (IMT) systems are mobile broadband systems encompassing IMT-2000, IMT-Advanced and IMT-2020.

IMT-2000 provides access through one or more radio links to a wide range of telecommunications services supported by fixed telecommunications networks (e.g. public switched telecommunication network (PSTN)/Internet) and other services specific to mobile users. Since the year 2000, IMT-2000 has continuously improved. Recommendation ITU-R M.1457, which provides the detailed radio interface specifications for IMT-2000, has also been updated accordingly. New features and technologies have been introduced to improve the capabilities of IMT-2000.

IMT-Advanced is a mobile system that can support high-quality multimedia applications across a wide range of services and platforms. The system provides a significant improvement in performance and quality relative to IMT-2000. IMT-Advanced systems can operate in low to high mobility conditions over a wide range of data rates in multiple user environments according to user and service demands. Such systems provide access to a wide range of telecommunication services, including advanced mobile services, which are supported by packet-based mobile and fixed networks. Recommendation ITU-R M.2012 provides the detailed radio interface specifications of IMT-Advanced, and it also has been updated accordingly.

IMT-2020 includes new capabilities of IMT that go beyond those of IMT-2000 and IMT-Advanced. These new capabilities make IMT systems more efficient, fast, flexible and reliable when providing a variety of services. Diverse usage scenarios were introduced in IMT-2020 such as enhanced mobile broadband (eMBB), ultra-reliable low-latency communications (URLLC) and massive machine-type communications (mMTC). Besides significantly enhancing the data rate and mobility provided in IMT-Advanced, IMT-2020 introduced advantages such as spectrum efficiency, latency, reliability, connection density, energy efficiency and area traffic capacity to efficiently support emerging usage scenarios and applications. Recommendation ITU-R M.2150 provides the detailed radio interface specifications of IMT-2020.

ITU-R studied technology trends that led to the development of IMT-Advanced and IMT-2020, and the results were documented in Reports ITU-R M.2038 and ITU-R M.2320, respectively. Since the publication of Report ITU-R M.2320 in 2014, there have been significant advances in IMT technologies and the deployment of IMT systems. The capabilities of IMT systems are being continuously updated in line with user trends and technological developments. Accordingly, this Report provides information on the technology trends of terrestrial IMT systems considering the time frame up to 2030 and beyond such as emerging technology trends and enablers, technologies to enhance the radio interface, and technology enablers to enhance the radio network.

2 Scope

This Report provides a broad view of future technical aspects of terrestrial IMT systems considering the time frame up to 2030 and beyond, characterized with respect to key emerging services, applications trends and relevant driving factors. Technologies described in this Report are collections of potential technology enablers which may be applied in the future. It comprises a toolbox of technological enablers for terrestrial IMT systems, including the evolution of IMT through advances in technology and their deployment. This Report does not preclude the adoption of any other existing technologies and emerging technologies expected in the future.

3   Related ITU-R documents

3.1   ITU-R Recommendations

Recommendation ITU-R M.1457

Recommendation ITU-R M.2012

Recommendation ITU-R M.2150

3.2   ITU-R Reports/Questions

Report ITU-R M.2320

Report ITU-R M.2330

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4   Overview of emerging services and applications

The development of IMT systems for 2030 and beyond calls for a thorough reconsideration of several types of interactions. The roles of modularity and complementarity of new technological solutions become increasingly important in the development of increasingly complex systems. The use of data and algorithms such as artificial intelligence (AI) will play an important role, and technological complementarities are required to ensure that the technology innovations complement each other. This is particularly important as the role of IMT-2030 and beyond can be seen as a pervasive general-purpose system, instead of simply an enabling technology, resulting in complex technical dependencies.

In this section, a summary information of emerging services and applications is presented to explain the need and motivation of corresponding technology developments.

4.1   New services and application trends

The role of the users of new services and applications is important in the technology development for IMT towards 2030 and beyond, and users will need to have access to the services, required devices, as well as the knowledge to use them. Users' opportunities to actively participate as experientials and developers will increase through a deeper understanding of technologies and skills allowing to shape the technologies for personalized needs. In particular, the role of IMT towards 2030 and beyond can be considered a pervasive general-purpose system instead of a simple enabling technology, resulting in complex technical dependencies.

New services and application trends for IMT towards 2030 and beyond can be summarized as follows:

–   Networks will support enabling services that help to steer communities and countries towards reaching the United Nations' Sustainable Development Goals (UN-SDGs)

–   Customization of user experience will increase with the help of user-centric resource orchestration models

–   Localized demand–supply–consumption models will become prominent at a global level

–   Community-driven networks and public–private partnerships will bring about new models for future service provisioning

–   Networks will have a strong role in various vertical and industrial contexts

–   Market entry barriers will be lowered by the decoupling of technology platforms, enabling for multiple entities to contribute to innovations

–   Empowering citizens as knowledge producers, users and developers will contribute to a process of human-centred innovation, contributing to pluralism and increased diversity

–   Privacy will be strongly influenced by increased platform data economy or sharing the economy, emergence of intelligent assistants, connected living in smart cities, transhumanism, and digital twins

–   Monitoring and steering of circular economy will be possible, helping to create a better understanding of sustainable data economy

–   Sharing and circular economy-based co-creation will enable the promotion of sustainable interaction with existing resources and processes

–   Development of products and technologies that innovate to zero will be promoted; for example, zero-waste and zero-emission technologies

–   Immersive digital realities will facilitate novel ways of learning, understanding and memorizing in several fields of science.

The role of IMT towards 2030 and beyond will be to connect many devices, processes and humans to a global information grid cognitively, thereby offering new opportunities for various verticals. Considering their different development cycles, a full complement of potential advances and vertical transformations will continue in the post-2030 era. The trend towards higher data rates will continue leading up to 2030, where peak data rates may approach Tera bits per second (Tbit/s) indoors, requiring large available bandwidths giving rise to (sub-) Tera hertz (THz) communications. At the same time, a large portion of the vertical data traffic will be measurement-based or actuation-related small data. In most cases, this will require extremely low latency in tight control loops, which may necessitate short over-the-air latencies to allow time for computation and decision making. Simultaneously, the reliability and the QoS requirements in many vertical applications will increase so that required services are available in the areas where it is needed. Industrial devices, processes and future haptic applications, including multi-stream holographic applications will require strict timing synchronization with tight requirements for jitter.

4.1.1   Potential new services, trends and opportunities

The three usage scenarios described in IMT-2020, eMBB, mMTC and URLLC will still remain relevant. New use cases and applications should be considered for continuing evolution, especially for those driving the technologies development and reflecting the future requirements. Consequently, the following new services are envisioned as trends and opportunities:

–   Holographic communication

        Holographic displays are the next evolution in multimedia experience delivering 3D images from one or multiple sources to one or multiple destinations, providing an immersive 3D

experience for the end user. Interactive holographic capability in the network will require a combination of very high data rates and ultra-low latency.

–   Tactile and haptic Internet applications

Human operators can monitor the remote machines by virtual reality (VR) or holographic-communications, and are aided by tactile sensors which may also involve actuation and control via kinaesthetic feedback.

Tele-diagnosis, remote surgery and telerehabilitation are just some of the many potential applications in healthcare. Tele-diagnostic tools, medical expertise/consultation could be available anywhere and anytime regardless of the location of the patient and the medical practitioner. Remote and robotic surgery is an application where a surgeon gets real-time audio-visual feeds of the patient that is being operated upon in a remote location. The technical requirements for haptic internet capability cannot be fully provided by current systems.

–   Network and computing convergence

Mobile edge computing (MEC) will continue being deployed towards future IMT networks. When clients request a low latency service, the network may direct this to the nearest edge computing site. Augmented reality/virtual reality (AR/VR) rendering, autonomous driving and holographic type communications are all candidates for edge cloud coordination.

–   Extremely high-rate access

Access points (APs) in transport nodes, shopping malls, and other public places may form information access points. These access points will provide fibre-like speeds. They could also act as the backhaul needs of millimetre-wave (mmWave) small cells. Co-existence with cellular services as well as security appears to be the major issue requiring further attention in this direction.

–   Connectivity for Everything

Scenarios include real-time monitoring of buildings, cities, environment, cars and transportation, roads, critical infrastructure, water and power amongst others. The Internet of bio-things through smart wearable devices, intra-body communications achieved via implanted sensors will drive the need of connectivity much beyond mMTC.

It is anticipated that Private networks, applications, or vertical-specific networks, Internet of Things (IoT) sensor networks will increase in numbers in the coming years. Interoperability is one of the most significant challenges in such a ubiquitous connectivity/compute environment (smart environments), where different products, processes, applications, use cases and organizations are connected. Interactions among telecommunications networks, computers and other peripheral devices have been of interest since the earliest distributed computing systems.

Vehicle-to-vehicle (V2V) or vehicle-to-infrastructure (V2I) communication and coordination, autonomous transport can result in a reduction of road accidents and traffic jams. Latency in the order of a few milliseconds will likely be needed for collision avoidance and remote driving.

–   Extended Reality (XR) – Interactive immersive experience

This interactive immersive experience use case will have the ability to seamlessly blend virtual and real-world environments and offer new multi-sensory experiences to users. Extended Reality (XR), such as virtual reality (VR), augmented reality (AR) and mixed reality (MR) is expected to provide higher resolution, larger field of view, higher frames per second and lower motion-to-photon, which all translate into higher demand on the transmission data rate and end-to-end latency.

A key challenge to address when supporting interactive experiences in network include synchronized transport of multi-modality of flows (e.g. visual media, audio, haptics) to and from different devices in a collaborative group serving the same XR application. Another important consideration is supporting real-time adaptations in the network relative to user movements and actions to ensure the interactions with other users and objects appear highly realistic in terms of placement and responsivity. Enabling spatial interactions will also require fast accessibility and ease of integration of content containing up-to-date and accurate representations of real/virtual environments from different content sources.

– Multidimensional sensing

Sensing based on measuring and analysing wireless signals will open opportunities for high-precision positioning, ultra-high-resolution imaging, mapping and environment reconstruction, gesture and motion recognition, which will demand high sensing resolution, accuracy, and detection rate.

– Digital Twin

Digital twin is a digital replica of entities in physical world, which demands real time and high accuracy sensing to ensure the accuracy, and low latency and high data transmission rate to guarantee the real time interaction between virtual and physical worlds. It could be capable of generating perceptive and cognitive intelligence based on collection of historical and on-line network data. It may also be capable of continuously seeking the optimal state of the physical network in advance and enforcing management operations accordingly.

– Machine Type Communication

Enabling efficient Machine Type Communication (MTC) continues to be an important driver for IMT towards 2030 and beyond. It allows machines and devices to communicate with each other without direct human involvement. MTC is a major driver behind the Internet of Things (IoT) and the future digitalization of economies and society. MTC encompasses critical MTC (cMTC) and massive MTC (mMTC). cMTC targets mission-critical connectivity with stringent requirements on key performance indicators (KPI) such as reliability, latency, dependability, and synchronization accuracy. On the other hand, mMTC addresses connectivity needs for massive number of potentially low-rate, low-energy simple devices, where the connection density and the energy efficiency are the most important KPIs.

– Proliferation of intelligence

Real-time distributed learning, joint inferring and collaboration between intelligent robots demand a re-thinking of the communication system and networks design.

– Global Seamless Coverage

To connect the unconnected and provide continuously high quality mobile broadband service in various areas, it is expected that a number of technology solutions and their combinations are needed. Additionally, the interconnection of terrestrial and non-terrestrial networks may facilitate the provision of such services.

4.1.2 Diversification of terminals

Until now, humans have been the main consumers of data. However, the appearance of intelligent smart machines, which also consume a significant volume of data is now witnessed. Moreover, it is also expected that various types of terminals in the form of wearables, skin-patches, bio-implants and exoskeletons can be combined with state-of-the-art man-machine interfaces, such as gestures, haptics, and brain sensors, to expand and become new industries. While smartphones remain, non-portable terminals such as cars, Unmanned Aircraft Systems (UASs), vessels and robots equipped with multisensory integration and intelligent capabilities, are expected to play an increasingly significant role

in every field of the future society. The diversification of terminals will lead new verticals to emerge and thrive.

4.2   Drivers for future technology trends towards 2030 and beyond

The continuing evolution of the IMT systems and the underlying technologies must be guided by the imperative to satisfy fundamental requirements and contextualized in terms of how they can help society, the end users, and value creation/delivery. These necessities and key driving factors are as follows:

–   Societal goals – Future technologies should contribute further to the success of several UN-SDG goals including environmental sustainability, efficient delivery of health care, reduction in poverty and inequality, improvements in public safety and privacy, support for aging populations and managing expanding urbanization.

–   Market expectations – new technologies should enable significant and novel capabilities, support radically new and differentiated services, and create greater market opportunities.

–   Operational necessities – The need to manage complexity, drive efficiency and reduce costs with end-to-end automation and visibility is also an imperative motivation and driving factor.

Key drivers for IMT Systems for 2030 and beyond include:

–   Energy efficiency

   Energy efficiency has long been one important design target for both network and terminal. While improving the energy efficiency, the total energy consumption should also be kept as low as possible for sustainable development. Power efficient technology solutions are needed both in backhaul and local access to make use of small-scale renewable energy sources.

–   Data Rate, Latency and Jitter

   The data rate for future systems should be increased as much as practical in order to support extremely high bandwidth services such as extremely immersive XR and holographic communications.

   Services with real-time and precise control usually have high demands on the latency of communications, such as the air interface delay, end-to-end latency, and roundtrip latency.

   Jitter refers to the degree of latency variation. Some of the future services such as time sensitive industry automation applications may request the jitter close to zero.

   Future system should guarantee users' experience regardless of users' location and network traffic conditions.

–   Sensing resolution and accuracy

   Sensing based services, including traditional positioning and new functions such as imaging and mapping, will be widely integrated with future smart services, including indoor and outdoor scenarios. Very high accuracy and resolution will be needed to support a better service experience.

–   Connection density

   Refers to the number of connected or accessible devices per unit space. It is an important indicator to measure the ability of mobile networks to support large-scale terminal devices. With the popularity of the IoT and the diversification of terminal accesses in the specific applications such as industrial automation and personal health care, mobile systems need to have the ability to support ultra-large connections.

–   Coverage and full connectivity

The future network should be able to provide global coverage and full connectivity with heterogeneous multi-layer architecture. The full connectivity network should support intelligent scheduling of connectivity according to application requirements and network status to improve the resource efficiency and service experience. It will extend the provision of quality guaranteed services, such as MBB, massive IoT, high precision navigation services, from outdoor to indoor from urban to rural areas and from terrestrial to non-terrestrial spaces.

–   Mobility

Refers to the maximum speed supported under a specific Quality of Service (QoS) requirement. Future systems will not only support terminals on land (e.g. high-speed train), but also provide services to terminals in airplanes, drones and so on.

–   Spectrum utilization

With new services and applications towards 2030 and beyond, more spectrum may be required to accommodate the explosive mobile data traffic growth. Further study may be introduced on novel usage of low and mid band, and the extension to much higher frequency bands with broader channel bandwidth. The smart utilization of multiple bands and improvement of spectrum efficiency through advanced technologies are essential to achieve high throughput in limited bandwidth.

–   Simplified user-centric network

With huge amounts of new services and scenarios towards 2030 and beyond, the network is required to satisfy diversified demand and personalized performance. The concept of soft network was proposed as a fully service-based and native cloud-based radio access network (RAN), which can guarantee the QoS and provide consistent user experience. The simplified user-centric network is a globally unified access network with the simple architecture and the powerful capabilities of robust signalling control, accurate network services and efficient transmission through the converged communication protocols and access technologies with plug-and-play, on-demand deployment. A user-centric network enabling a fully distributed/decentralized network mitigates a single point of failure as well as to enable the user-controlled data ownership which is critical to the next generation network.

–   Native Artificial Intelligence (AI)

The future mobile system should have stronger capabilities and support more diversified services, which will increase the complexity of the network. AI reasoning will be native wherever it is required in the future network including physical (PHY) layer design, radio resource management (RRM), network security and application enhancement, as well as network architecture, which results in a multi-layer deep integrated intelligent network design. The future network is also expected to support distributed AI as a service for larger scale intelligence.

–   Security/Trustworthiness

A future network may support more advanced system resilience for reliable operation and service provision, security to provide confidentiality, integrity and availability, privacy with self-sovereign data and safety regarding the impact to the environment.

The roles of trust, security and privacy are somewhat interconnected in various facets of future networks. Inherited and novel security threats in future networks should be addressed. Diversity and volume of novel IoT and other networked devices and their control systems will continue to pose significant security, privacy risks and additional threat vectors when moving to IMT towards 2030 and beyond. IMT towards 2030 and beyond should strive to support embedded end-to-end trust such that the level of information security in networks is

significantly better than today's network. Trust modelling, trust policies and trust mechanisms need to be defined.

Security algorithms may use machine learning (ML) to identify attacks and respond to them. Continuous deep learning on a packet/byte level and machine learning can enforce policies, detect, contain, mitigate, and prevent threats or active attacks.

–   Dynamically controllable radio environment

A dynamically controllable radio environment may be able to change the characteristics of the radio propagation environment, therefore creating favourable channel conditions to support higher data rate communication and improve coverage.

5   Emerging technology trends and enablers

5.1   Technologies for AI-native communications

The success of AI in image, video and audio signal processing, data mining and knowledge discovery amongst others has made it possible to shift wireless communication to an intelligent paradigm. More specifically, architectures, protocols and algorithms for the IMT towards 2030 and beyond will be designed by learning from wireless big data which has yet to be comprehensively exploited. In turn, with the wide deployment of base stations (BSs), edge servers and intelligent devices, mobile networks will provide a novel and powerful platform for ubiquitous data collection, storage, exchange, and computing which are potential enablers for future mobile distributed/collaborative ML. For the future communication system, an innovative and transformative shift will provide the access of AI to everyone, every business, every service anywhere anytime. AI is the design tablet of the future communication system, and it will be the cornerstone to create intelligence everywhere. One of the main differences between the future communication systems relative to IMT-2020 is that it will use mobile technologies to enable the proliferation of AI and utilize the radio networks to augment ubiquitous, distributed ML.

5.1.1   AI-native air interface

Applying tools from AI and ML, and its sub-set deep learning, in wireless communications have gained a lot of traction in recent years. This trend in large part has been motivated by the significant increase in the system complexity in the IMT-2020 RAN and its evolution over previous wireless technology generations. Deep neural networks allow the characterization of specific or even unknown channel environment and network environment, i.e. the traffic, the interferences and user behaviours, and then adapt the radio signalling to the channel and network environment. With learning it can optimize user signalling, power consumption as well as its end-to-end connectivity, and smartly coordinate the multi-user access of radio resources, thus optimizing the data and control plane signalling and improving the overall system performances.

Sensing communication environment is the most challenging issue in air interface design, i.e. the estimation and prediction of propagation channels. To this end, traditional air interface pays much effort to pilot design and channel estimation. Now with ML and especially the capability of black-box modelling and hyper-parameterization of a deep neural network, the unknowns of the underlying channel could be properly learned provided that sufficient data is available. The learned model can be transferred to adjacent nodes via transfer learning. It provides new way to air interface design. Several components in the transceiver chain are expected to be implemented through AI/ML based algorithms. It includes the transmitter (TX) side – beamforming and management and the receiver (RX) side – channel estimation, symbol detection and/or decoding. Therefore, there will be an emphasis on redesigning the PHY layer of the communication protocol stack using AI. However, the

implementation issues related to the periodic updating of deep learning models used in various blocks of the PHY layer must be addressed.

Examples of the proposed areas to be investigated are presented next.

AI in symbol detection/decoding: ML techniques can be used for symbol detection and/or decoding. While de-modulation/decoding in the presence of Gaussian noise or interference has been studied for many decades, and optimal solutions are available in many cases, ML could be useful in scenarios where either the interference/noise does not conform to the assumptions of the optimal theory, or optimal solutions are too complex. Meanwhile, IMT towards 2030 and beyond is likely to utilize even shorter codewords than IMT-2020 with low-resolution hardware, which inherently introduce non-linearity that is difficult to handle using classical methods. Accordingly, ML could play an important role in symbol detection, precoding, beam selection, and antenna selection.

AI in channel estimation: Another promising area for ML is the estimation and prediction of propagation channels. IMT systems of prior generations have mostly exploited channel state information (CSI) at the receiver, while CSI at the transmitter was mostly based on roughly quantized feedback of received signal quality and/or beam directions. In systems with even larger number of antenna elements, wider bandwidths and higher degree of time variations, the performance loss of these CSI feedback scheme is non-negligible. ML may be a promising approach to overcome such limitations.

AI in MAC layer design: Medium access control (MAC) layer is a major application area of AI where many problems with legacy solutions can be replaced with AI-based methods using supervised learning, data collection and ML model deployment. To jointly update the deployed ML models, collect data for supervised learning tasks and enable reinforcement learning on different blocks of the network, next generation MAC algorithms need to consider the coordination with AI functions used in various layers of the network, especially in PHY layer.

AI in radio resource management: Radio resource management or resource allocation can also be implemented via AI/ML based methods. In a multi-user environment, with reinforcement learning, BSs and UE can automatically coordinate the channel access and resource allocation based on the signals they respectively received. Each node calculates its reward for its transmission, and adjusts its power, beam direction and other signalling to accomplish the distributed interference coordination and improve the system capacity.

Semantic communications: With the progresses of ML and information theory, the ultimate air interface can perform the automatic semantic communications. There are many open fundamental problems in this issue. For example, learning algorithms usually relies highly on the wireless data which may be hard to obtain or be preserved under privacy constraints. To solve it, it is possible to learn with both the practical wireless data and the statistical models.

Questions related to the optimal ML algorithms given certain conditions, required amount of training data, transferability of parameters to different environments, and improvement of explainability will be the major topics of research in the foreseeable future. There will be various phases towards development of AI for radio interface technologies, and it is imperative to ensure the increased integration of the technology comes with minimum disruption to the rollout and operation of radio interface technologies. In the short and medium terms, AI models can target for optimization of specific features within radio interface technologies for IMT-2020 and its evolution. In the longer term, AI can be used to enable new features over legacy wireless systems.

5.1.2 AI-native radio network

Future IMT-systems must support extremely reliable and performance-guaranteed services. They will introduce a multi-dimensional network topology, which will make network management and operation more difficult and introduce more challenging problems. To address these problems, AI

technologies can be adopted for automated and intelligent networking services. Consequently, radio access network for IMT towards 2030 and beyond will evolve into an AI-native network architecture to assist computationally intensive tasks.

The highest level of AI-native radio network is expected to be designed and implemented by AI to act as an intelligent radio network, which can automatically optimize and adjust the network based on the specific requirements/objectives/commands, or environmental changes. The research includes high-layer protocols, network architecture and networking technologies enabling intelligent radio network.

Numerous use cases of AI-empowered network automation have been proposed, including fault recovery/root cause analysis, AI-based energy optimization, optimal scheduling, and network planning. Key challenges of training issues have been identified: lack of bounding performance, lack of explainability, uncertainty in generalization and lack of interoperability to realize full network automation. Four types of analytics can be classified for future AI-native networks: descriptive, diagnostic, predictive and prescriptive analytics.

The future RAN will be able to perceive and adapt to complex and dynamic environments by monitoring and tracking conditions in the radio network while diagnosing and restoring any RAN issues in an automated fashion. To achieve autonomy for its full life cycle management, at least the following novel networking technologies could be considered: 1) efficient and intelligent network telemetry technologies that leverage AI to apply management operations based on a collection of historical and live network data; 2) automated network management and orchestration technologies that continuously seek the optimal state of the RAN and enforce management operations accordingly; 3) automatically perform life cycle management operations, adjust configurations on radio network elements, and optimize new services and features during and after deployment; and 4) provide AI based assistance, in particular for aspects such as forecasting, root cause analysis, anomaly detection and intent translation.

Examples of the proposed areas to be investigated are presented next.

Intelligent data perception: Large quantity of data transportation will bring burdens to each network interface. Besides, data sensed from the radio environment sometimes do not have the corresponding labels. Intelligent data perception, e.g. utilizing Generative Adversarial Networks (GAN) to generate the required data so as to simulate real data, will avoid transferring large amount of data over interfaces, and protect the data privacy to a certain degree. To further this vision of zero-touch network management, an open network data set and open eco-system could be established.

Introducing user feedback: It is also possible that user feedback is introduced into the decision-making process of the network to improve the decision-making of AI algorithms and help the machine to better understand user preferences and make more user-preferred decisions.

Pervasive computation nodes: In future IMT-systems, more computation nodes will be required to support highly computationally intensive services. Thus, computation nodes will be pervasive from core to edge and from network to device. To cope with this trend, the control and user planes of the network for future IMT-systems could be redesigned, and emerging technologies such as programmable switches and distributed/federated learning could be adopted.

Supply of on-demand capability: To support services in multiple application scenarios, an intelligent network is needed. In the AI-native Radio Network, AI is no longer just optimizing the wireless resources of the wireless network, but an intelligent system integrating with radio network, which can realize the supply of on-demand capability.

Collaboration of sensing and AI: In order to realize the intelligence of Radio Network, the new functions of sensing and AI need to be supported. The end-to-end collection, processing and storage of network data can be realized through the data sensing function. AI function can use these data on

demand to support different application scenarios. In this way, the utilization and support of AI capabilities can be realized more efficiently and globally.

Distributed and unified AI control: AI system in AI-native radio network is expected to be distributed over various network functions. For example, AI algorithms running on different functions or AI models trained on different functions are integral components of this distributed AI system. There should be a unified AI control centre for the distributed AI system, and under the control or coordination of this AI control centre, each component of the distributed AI system independently completes the assigned tasks, interacts with other components and reports measurements to the control centre. By doing this, distributed AI system is expected to be an end-to-end solution.

Adaptive solutions for different usage: AI techniques can be used to target one or more wireless domains, including non-real-time network orchestration and management, such as configuration of antenna parameters and near-real-time network operation, e.g. load balancing and mobility robustness optimization. Each wireless domain involves different sets of physical and virtual components, family of parameters including KPIs, underlying complexities, and time constraints for updates. Hence, there is a need to consider tailored AI solutions for different classes of the RAN, and their associated problems. There already exists a rich body of research and practical demonstrations of the potential benefits of AI for wireless, including significant network energy savings.

5.1.3 Radio network to support AI services

The radio network will be migrated from over the top towards the AI era. Wireless networks should consider AI applications and paradigms that require the exchange of large volumes of data, ML models, and inference data between different entities in the networks. Long-term platform technologies are needed to better support AI services, which will have a significant impact on the design of future radio networks, i.e. radio network for AI. Distributed and collaborative ML is required to comprehensively exploit the computing/communication load and the efficiency and comply with the local governance of data requirements and data privacy. Hence, the data-split and model-split approaches will be emphasized in future research. The impacts of this on the future network design are threefold:

Shift from downlink (DL) -centric radio to uplink (UL) -centric radio: Unlike the current DL-centric radio which usually supports heavier traffic and better QoS for DLs, AI requires more frequent model and data exchanges between a BS and the users it serves. The ULs should be reconsidered in network design to attain a balanced, efficient, and robust distributed ML.

Shift from the core network to the deep edge: The locality of data and the computing/communication needed for deep ML bring big challenges to the end-to-end delay. To mitigate it, new network as well as the corresponding protocols should be redesigned. One of such research directions is to place the major learning processes and threads close to the edge and thus forms a deep edge which can greatly mitigate the system delay.

Shift from cloudification to ML: Due to the distributive nature of data and computing power, the communication and computing procedures of an ML algorithm often take place across the whole network from the cloud to the edge and the devices. Therefore, traditional cloudification should also be reconsidered to be application-centric, i.e. to meet the specific needs of the more general distributed ML applications with proper deployment of computing and communication resources.

In addition, future data-intensive, real-time applications require distributed AI/ML solutions. These solutions support augmenting human-decision processes, developing autonomous systems from small devices to complete factories, and optimising the network performance and marshalling the billions of IoT devices expected to be interacting in the future. Since heterogeneous IoT devices are not as reliable as high-performance centralized servers, distributed and self-organising schemes are essential to provide strong robustness in device and link failures. Currently there are still many open questions

in fulfilling the requirements of the true distributed AI/ML solutions, such as data and resource distribution, distributed and online model training, as well as AI inferring based on those models across multiple heterogeneous devices, locations and domains of varying context-awareness. The future network architecture is expected to provide native support for radio-based sensing and, through versatile connectivity, accommodate ultra-dense sensor and actuator networks, enabling hyper-local and real-time sensing and communication.

5.2   Technologies for integrated sensing and communication

Wireless sensing including object detection, ranging, positioning, tracking, imaging, etc, has long been a separate technology developed in parallel with IMT systems. Positioning is the only sensing service offered by IMT-2020 system. Departing from the traditional approach of designing wireless networks solely for communication purposes, IMT towards 2030 and beyond will consider an integrated sensing and communication (ISAC) system from its outset. In the future communication systems, enabled by new features such as the potential use of very high frequency bands (e.g. from mmWave up to THz), wider bandwidth, denser deployment, larger antenna arrays, as well as AI and collaboration between communication nodes/devices, sensing will become a new function integrated with the communication system to enable innovative services and solutions with higher degree of accuracy.

In the ISAC system, sensing and communication functions will mutually benefit within the integrated system. On the one hand, the communications system can assist the sensing services. More specifically, it can explore radio wave transmission, reflection and scattering to sense and better understand the physical world, which is also known as 'network as a sensor'. On the other hand, sensing results can be used to assist communication in access or control such as more accurate beamforming, better interference management, faster beam failure recovery and less overhead to track the CSI, both QoS efficiency of the communication system. It is known as 'sensing assisted communication'. Moreover, sensing can be regarded as a 'new channel' that link the physical world to the digital world. Thus, real-time sensing combined with AI technologies can also be essential to realize the digital twin.

In general, the interaction level between communication and sensing systems can be classified as (a) co-existence, where sensing and communication operate on physically separated hardware, use the same or different spectrum resources and do not share any information, treating each other as interference; (b) cooperation, where the two systems operate on physically separated hardware, while information can be shared to each other (e.g. prior knowledge of sensing/communication could be shared to reduce inter-system interference or in some case enhance the other system); and (c) integrated design, where the two systems are designed to behave as a single system with information sharing and joint design in spectrum usage, hardware, wireless resource management, air interface and signal transmission and processing amongst others. The focus of ISAC in future IMT is on (c).

In the integrated design, the technology development of the ISAC can be divided into different stages that can range from loosely coupled to fully integrated. As a starting point, communication and sensing system share resources such as spectrum and hardware. Communication and sensing can be implemented as a single system that simultaneously serves two traffic forms. Developing efficient scheduling and coordination algorithms between sensing and communication modules to minimize the interference to each other is a key research issue. As a step further, communication and sensing will work together to enhance the performance of a single system. The integration of signal processing, such as time, frequency and spatial domain processing techniques can be jointly designed to serve both sensing and communication. Potential directions in this stage would include air interface design based on a joint waveform, unified beamforming scheme and others, which is essential to improve the efficiency of the ISAC system. Towards the mature stage of the ISAC, communications and sensing will be coordinated and collaborated in all possible dimensions including spectrum,

hardware, signalling, protocol, networking and others, achieving mutual promotion and benefits. Further combined with technologies such as AI, network cooperation and multi-nodes cooperative sensing, the ISAC system will have benefits in enhanced mutual performance, overall cost, size and power consumption of the whole system.

The capabilities of ISAC enable many new services which the mobile operators can offer, including but not limited to extremely high accuracy positioning, tracking, imaging (e.g. for biomedical and security applications), simultaneous localization and mapping, pollution or natural disaster monitoring, gesture and activity recognition, flaw and materials detection. These capabilities enable application scenarios in future consumer and vertical applications in all forms of business such as context-aware immersive human-centric communications, industrial automation, connected automated vehicles and transportation, energy and healthcare/e-health.

Communication and sensing services need to share available hardware and waveforms while fusing information from distinct sources of measurements in the network deployment area. Research challenges remain in areas such as system level design and evaluation methodologies to characterize the fundamental trade-offs of the two functions in the integrated system, the solutions to deal with the increased sensitivity to hardware imperfections, joint waveform design and optimization and others.

5.3   Technologies to support convergence of communication and computing architecture

Computing services and data services are expected to become an integral component of the emerging IMT system for 2030 and beyond, since important use cases include digital twin, cyber-physical systems, MR, and industrial/service robots. To address the challenging issues in implementing these use cases to support the convergence of communication and computing architecture, several emerging technology trends are envisioned.

One such trend is processing data at the network edge close to the data source for real-time response, low data transport costs, energy efficiency, and privacy protection. Accordingly, edge computing is a distinguished form of cloud computing that shifts part of the service-specific processing and data storage from the central cloud to edge network nodes that are physically and logically close to the data providers and end-users. Performance improvements, traffic optimization and new ultra-low latency services are among the expected benefits of edge-computing deployment in existing networks. Edge intelligence in IMT towards 2030 and beyond will significantly contribute to all the aforementioned aspects, which can be useful for having computational tasks that follow mobile users, opportunistically offloading workloads from the device to preserve device energy and moving computations for an optimized cost/performance/power trade-off.

Furthermore, scaling out device computing capability beyond its physical limitations for advanced application computing workloads is another trend. Future applications, such as truly immersive XR, mobile holograms and digital twin require extensive computational capabilities to deliver real-time immersive user experiences. However, it is challenging to meet such computational requirements solely with mobile devices. Split computing makes use of reachable computing resources over the network to overcome the limits of the computing power of mobile devices. These computing resources could be available on various entities of networks, e.g. mobile devices, BSs, MEC servers and cloud servers. With split computing, mobile devices can effectively achieve higher performance even as they extend their battery life, as devices offload heavy computation tasks to computation resources available in the network. The realization of holographic communications poses significant challenges ranging from signal generation to advancement in display technology. Current holographic displays are limited to head-mounted display technology only and offer limited three-dimensional effects without accounting for several cues of the human visual system. As for using a mobile device to experience a hologram, there are additional graphics processing units (GPUs) and battery life limitations requiring significant improvement to meet the future service requirements of holograms.

These new technological trends present new technology challenges related to scalability, dynamic workload distribution, and data collection/management/sharing. Scalability is one such challenge. In modern cloud computing, computing resources are often centralized in a few national or regional data centres. Centralized service discovery and orchestration mechanisms are given full visibility of computing resources and services in data centres. The centralized approach is no longer scalable when computing resources and services become more widely distributed. Therefore, a more scalable approach is required for widely distributed computing resources.

Dynamic computing workload distribution is another challenge. Modern workload distribution between devices and the cloud is based on a client-server model with a fixed workload partition between a client and the cloud. The fixed workload partition is application-specific and is pre-determined during the application development phase under the assumption that there are always sufficient computing resources in the cloud to accomplish the server-side workload. As computing resources become distributed, a scheme is needed to allow dynamic device computing scaling out based on various network conditions, such as workload requirements and communication computing resource availability. A dynamic computing scaling scheme can be enabled as an IMT system capability with minimal dependency on applications to minimize the impact on them.

Additional challenges are data collection, synchronization, processing, management and sharing. More specifically, with the widespread application of AI in society/industry, a systematic approach to collecting, processing, managing and sharing data to facilitate AI/ML is vital. Split computing also requires the synchronization of a large volume of data, context, and the software among network entities. Conventional data management functions in cellular networks focus on managing subscription information and policies. In IMT-2020, a network data analytics function was added to the specifications through which the measurement data of network functions can be collected and used for analytics. It is expected that future IMT towards 2030 and beyond will have further diversification on data sources, types, and consumptions. Therefore, it is expected that data plane functions will be part of the IMT system function from the beginning and would provide support to full-blown data services to devices, network functions and applications.

5.4   Technologies for device-to-device communications

5.4.1   Sidelink communications

Device-to-device (D2D) wireless communication with extremely high throughput, accurate positioning and low latency will function as an important communication paradigm for IMT towards 2030 and beyond. A multitude new applications, such as ultimate immersive cloud XR, holographic display, tactile internet with remote motion control, vehicle (terrestrial vehicles, unmanned aerial vehicles) related communications and sidelink enhanced industry internet of things (SL-IIoT), which need either Tbit/s throughput or sub-ms level latency and low power consumption wireless link, are expected to mature in the next decade and the wireless communication distance for these D2D applications are comparatively short. On the other hand, to satisfy the above wireless requirement, extremely wide bandwidth technologies with short propagation distance, such as THz technology, optical wireless technology, ultra-accuracy sidelink positioning technology, and enhance terminal power reduction technology, may be potential candidates. Therefore, how to integrate these short range D2D applications and its related sidelink technologies into cellular system need to be considered in the future communication system.

The sidelink communication by nature can significantly increase the system capacity. THz and optical wireless links have very narrow beams and short transmission distances. Therefore, the spectrum can be reused by other sidelinks, which can increase the system capacity. Meanwhile, a dynamic self-organized short-range network, such as a mesh network, can also solve the bottleneck of previous cellular systems in which all the resources on the air interface are managed centrally by a BS. However, the D2D or multi-hop short range mesh network may have the risk of slow convergence

time and significant signalling overhead caused by the frequent movement of nodes. Therefore, the integrated design of short range and cellular may help the sidelink to achieve optimized system level performance. How to increase the integration efficiency, as well as how it can co-exist with other systems on the same spectrum need further research.

5.4.2 Cooperation with peripheral devices

In the subjected technology, a UE is connected to its peripheral devices by using THz broadband radio, while the peripheral devices receive/transmit data signal in THz band radio with UE and also receive/transmit data signal in the different (lower) frequencies connecting to BSs (operated in, e.g. the mmWave bands and the sub-6 GHz bands) and then connect to the APs located in BS. Here, the peripheral devices play a role to mediate between a UE and BS with AP.

Generally, the THz radio has been investigated for use in fixed and long-range radio applications such as wireless backhaul, but the range depends upon path loss, antenna gains and rain fading. However, it is expected that the THz radio application could also be disseminated in the form of these short-range use cases.

In achieving the exchange of information with sufficiently high quality and quantity to satisfy the diverse user demands of individuals, UEs present significant limitations in terms of their size, which limits the number of integrated antennae and their maximum transmission power. It is impractical to increase the size of UEs to alleviate constraints such as the number of antennae, and the performance of UL communication is vastly inferior to DL communications.

Therefore, a cooperation technique between various peripheral devices that communicate with UEs is needed. Specifically, through the cooperation, it would be possible to solve issues arising from the constraints caused by a single user device, such as power transmission and the number of integrated antennae. For examples, peripheral devices around UEs, such as PCs, watches, glasses (smart glasses), or self-driving cars, can become wireless devices and cooperate with each other, making it possible to overcome transmission power constraints in a single user terminal, and to virtually overcome limitations in the number of antennae. When riding in a car with a UE, the antenna on the car can also be used virtually as the UE's antenna to enhance the communication performance.

Typically, communication between a UE and its peripheral devices requires a short-range but extremely wideband signal transmission. Since the capabilities required for wireless signal processing are limited in small devices such as watches and glasses, complex wireless signal processing should be avoided. Therefore, it is expected that the above-mentioned technology will be introduced.

5.5 Technologies to efficiently utilize spectrum

It is expected that the spectrum for future IMT systems will continue to utilize a mixture of different frequency bands as in current IMT systems, but with potentially larger bandwidths and higher operating frequencies. These bands can be jointly utilized to provide various wireless links of different bandwidths and beam-propagation characteristics that satisfy a wide range of use cases' requirements of future IMT systems. Moreover, it is also envisioned that the diverse future use cases, due to their different downlink (DL) and uplink (UL) system requirements, can be better met by using the propagation and bandwidth characteristics of these different frequency bands.

Spectrum utilization can be further enhanced by efficiently managing resources through different technologies such as advanced carrier aggregation (CA) and distributed cell deployments (distributed MIMO). Higher bandwidths can be achieved by enabling a device to simultaneously and flexibly connect to a set of available carriers, and steering the usage of available bands towards best efficiency. In distributed MIMO, a set of network nodes enables high-density deployment and spectral reuse. It allows for efficient antenna and transport solutions to utilize spectrum resources through central coordination.

5.5.1   Spectrum sharing technologies

Spectrum sharing refers to when two or more radio systems operate in the same frequency band. Two forms of spectrum sharing are currently present: 1) spectrum sharing between systems with the same level of access rights to the spectrum; and 2) spectrum sharing between systems with different levels of access rights to the spectrum. These methods of spectrum sharing are not mutually exclusive. Existing IMT systems involve various combinations of spectrum sharing through different techniques for interference mitigation. The same is expected in IMT towards 2030 and beyond.

One of the key aspects in advancing spectrum sharing is to natively develop IMT technologies capable of making use of databases, spectrum sensing, software defined radios, and reconfigurable radio networks, among others. These aspects are expected to play important roles in addressing the demand for next generation wireless services while enabling the broadband connectivity and digital inclusion in underserved areas. Improving receiver susceptibility to interference would be a key enabler for spectrum sharing, especially between different radio systems, and spectrum utilisation efficiency improvements.

It is desired that IMT systems for 2030 and beyond would enable a smooth transition from previous IMT technologies, while maintaining optimum use of spectrum resources. IMT towards 2030 and beyond should facilitate co-existence with the current IMT technologies to enable the same spectrum to be used by different IMT technologies, while balancing the bandwidth used for each technology based on user demand.

5.5.2   Technologies for broader frequency spectrum

In general, IMT towards 2030 and beyond use cases will require spectrum from the low up to the very high (i.e. THz) frequency bands. The expected higher capacity demand in future networks drives the industry to look for broader bandwidths, not only in the THz bands but also in lower frequency bands where higher capacity needs to be combined with good coverage.

To achieve extreme high data rate and high-capacity communication exceeding the IMT-2020 peak data rate requirements, future IMT technologies may require wider bandwidth compared to IMT-2020, including bands from the low to the very high frequency bands. However, given the nascent nature of radio waves in the THz frequencies, it is necessary to conduct technical studies on these emerging new frequency bands to identify their radio propagation characteristics and establish their propagation model, as well as study how to utilize them based on various network configurations.

Regarding device technology, it is necessary to implement a digital signal processing circuit capable of supporting wider bandwidths, one or more digital-to-analogue converters (DACs), and analogue-to-digital converters (ADCs) at low cost and low power consumption. Additionally, antennas, filters, amplifiers, mixers and local oscillators that operate in high frequency bands must be developed to be compatible with massive MIMO's multiple antenna elements. Furthermore, radio frequency (RF) circuits must also be designed for high performance and much denser integration.

The radio access technologies for different bands for IMT systems from the low to the very high bands present common technical issues related to coverage and power efficiency. Single-carrier signal waveforms are preferred over orthogonal frequency division multiplexing (OFDM) signal in higher frequency bands as a radio technology owing to their power efficiency. When applying radio technologies, including integrated access and backhaul, to a wider range of areas, the significance of power-efficient radio technology like single carrier is likely to increase.

From semiconductor viewpoint, though complementary metal oxide semiconductor processes are promising for use in certain frequency bands from around 100 GHz, other alternatives can be considered because operation in these bands will require careful conditioning of the output power, phase noise, I/Q imbalance, and noise figure along with the semiconductor process reliability and

packaging. It is noteworthy that operating from around 100 GHz could require up to an order-of-magnitude more elements relative to arrays deployed in millimetre waves, which could pose design challenges.

5.6 Technologies to enhance energy efficiency and low power consumption

Future IMT systems are expected to support almost a trillion devices, primarily driven by the surge in demand for IoT devices that cover a wide variety of applications such as smart cities, smart industries, and smart homes. A critical category is power-constrained devices that are meant to be fixed for sustained periods, stretching into several years. Devices may be inaccessible, or it is difficult or expensive to reach them after installation. These devices may perform a wide range of functions such as asset tracking, supply chain logistics and infrastructure monitoring. Such devices may also include the category of Internet-of-Tags, which involves tracking, sensing, or actuation functions. Accordingly, the need to improve energy efficiency has given rise to the field of energy-efficient communications.

Future IMT devices could become energy neutral. They will use energy harvesting, where the device's operational energy is obtained from ambient sources in the form of light, vibrations, temperature fluctuations, or radio waves, providing the possibility for devices to not require a battery. Most RF energy harvesting devices are limited by two factors: (1) Quality of the receive antenna; (2) Efficiency of the RF rectifier for converting the RF signals into DC power, which will need be considered for the design of energy efficient systems going forward.

Low energy consumption issues can be considered from both the user device and the network's perspectives. Technological advances on various aspects will contribute to lowering devices' and network's power consumption. Some examples include applying AI/ML to optimize the network energy usage and make it closely follow the traffic dynamics, exploiting large reconfigurable intelligent metasurface to enhance coverage and thus reduce power consumption. The design and deployment of communication systems are also important for low energy consumption. Efficient low-overhead communications are appealing to save overhead-related energy. In addition, network densification, distributed antenna deployments, moving/flying transmitters can shorten the communication distances, lowering communications' energy consumption.

Current AI/ML frameworks are not optimized for low power operation due to the massive amounts of training data required by supervised/semi-supervised algorithms. To this end, AI algorithm accelerators are designed and implemented on silicon with the use of GPUs/FPGAs/ASICs, which are far from optimal, and need to have dataflow architectures allowing for low-power memory access underlaid with a distributed memory fabric combined with pipeline elements. On the device side, IMT-2020 systems have the reduced capability operation in devices which allows them to access signalling mechanisms with extremely low sleep mode power consumption (also known as idle consumption rate). Future IMT systems should continue this trend with further optimization on the device power consumption.

5.6.1 Backscattering communications

Backscattering technology is considered as an alternative approach for low power and low-cost communication. A device can send information by modulating and reflecting received wireless signals from ambient sources, without requiring power hungry transceivers, amplifiers, and other traditional communication modules. Thus, it is possible to achieve extremely low power consumption and low-cost communication through backscattering technology. It can harvest the energy of the ambient wireless signals and/or other energy for communication, and thereby achieve nearly zero power communication. Ambient Backscatter Communication is referred to as the backscattering communication system that exploits ambient RF signals to transmit information bits without active RF transmission. The key challenges for these backscattering technologies include interference

between backscattering signals and source signals, and limited communications range and data rates. Accordingly, the techniques for backscattering communication include modulation and channel coding, signal detection algorithms, interference coordination techniques, combinations with MIMO technology, multi-user access approaches and others.

5.6.2   On-demand access technologies

The on-demand passive device with triggered wakeup receiving chain is an alternative approach to resolve low power communication. The on-demand passive device would stay in sleeping mode with zero power consumption and will have the receiver waken up when the network sends the wakeup signals when data arrives, which turns on the transceiver to switch to the connected status. In particular, the zero-energy passive device for triggering wakeup would be useful for machine type communication, wearable devices, health devices, and general mobile phone. The next generation wireless system needs to design the network and control signal for this on-demand access.

Mobile devices can support on-demand network access based on backscattering technology to minimize power consumption. The receiver sensitivity is the main challenge of the on-demand network access with a passive wakeup device. It will limit the coverage of the passive wakeup device. To accommodate the low receiver sensitivity of the frond-end passive device, the wakeup signals need to transmit in much higher density compared to that of the traditional BS deployments. In addition to being difficult to accomplish the blank cover of on-demand network access, this requirement will increase the network energy consumption for tracking the mobile device with front-end wakeup passive devices. Moreover, the low receiver sensitivity would hinge the coverage and development of next generation wireless network.

5.7   Technologies to natively support real-time services and communications

Two technology components are considered to achieve real-time communications with extremely low latency. The first one is accurate time and frequency information shared in the terrestrial network. When network nodes are equipped with compact atomic clocks, their high holdover performance can dramatically reduce synchronization iterations. The high frequency accuracy obtained from the atomic clocks also reduces the frequency offset between transmitter and receiver, leading to the low bit error ratio particularly in high carrier frequency. The collection of the time differences among node clocks facilitates the estimation of more stable and robust time using the maximum likelihood method, and the result can be delivered back to each node for their self-corrections. Wireless space-time synchronization, where clocks are synchronized at pico-second level together with the determination of positions, is another method on which low latency communication protocol can be built with a capability of autonomous and distributed operations. Such synchronized network supports the schedule management in edge processing in mobile backhauls. The common time and frequency can be traceable to the standard time or frequency by linking one node to the precision time/frequency source. The second technology component is fine-grained and proactive just-in-time radio access which incorporates the extremely short transmission time intervals for the scheduling, leading to the reduction of the buffering and channel access delay.

The benefit of these two technologies can be further enhanced by adopting time-sensitive communications protocols, which enables the prioritization of latency-sensitive or mission-critical traffic, facilitating to real-time communications. Resource management can be supported by leveraging application-domain information on the predictability of actual resource requirements by considering the context and traffic characteristics. Periodic transmissions can be pre-scheduled with given and precise time boundaries while AI and ML tools can be used to schedule algorithms. Resource allocation for real-time communications may also span over a multi-dimensional solution space comprising multi-RAT, multi-link, etc. These would be managed by a dedicated real-time management function that would track resource needs, availability, and surrounding environment.

5.8 Technologies to enhance trustworthiness

To respond to the diverse needs of users in the era beyond IMT-2020, it is essential not only to make progress in technological innovation in terms of functionality and performance, but also to provide a network infrastructure that all stakeholders can use safely and securely. The latter depends on 'trustworthiness technologies' such as security, privacy and resilience. Future systems will be highly heterogeneous and will operate under unprecedentedly diverse constraints including power, latency and computational and memory resources. Emerging technologies will pose further challenges, as they expand the attack surface beyond anything witnessed so far. It is necessary to consider the extensive introduction of AI as well as the prospect of quantum computing. Moreover, potential controls at all layers, including the physical layer, need to be considered.

Enhancing trustworthiness can be considered in several aspects.

5.8.1 RAN privacy

The characteristics of future IMT networks will require sufficient RAN technologies to preserve user privacy. The technologies can be incorporated into the design of future IMT networks. For example, AI-enabled smart applications will require situational, context-aware and customized privacy solutions. Traditional privacy-preserving approaches may be unsuitable owing to a diverse and complex set of novel privacy challenges. So future IMT radio networks may consider supporting the use of potential solutions such as distributed ledger technologies, differential privacy approaches and federated learning (FL).

IMT towards 2030 and beyond technologies are expected to become pervasive in various new use cases. In this context, there will be a need to ensure security, privacy and trust solutions allowing for legitimate exchange of sensitive information through the network entities. Indeed, all stakeholders involved are accountable to establish and guarantee a security indicator for digital interactions in more general contexts.

5.8.2 Quantum technology with respect to the RAN

Quantum computing is an emerging technological paradigm that promises novel processing and computational opportunities, which can also compromise cybersecurity ciphers. Therefore, improved methods are needed to mitigate such security threats. A location-aware cryptographic system was proposed to guarantee post-quantum security. The ultimate value of a location-driven cryptosystem involves using the geographic location as an identity credential. Location-driven cryptography using lattices is efficient and lightweight, and it can be used to protect sensitive and confidential data in numerous critical situations that rely heavily on exchanging confidential data.

5.8.3 Physical-layer security technologies

Currently proposed, post-quantum cryptographic algorithms are computationally heavy. Furthermore, the trustworthiness of IMT networks, such as those supporting cyber-physical systems, including digital twins, robots and drones, require adaptive security levels. In this context, physical layer security (PLS) solutions become attractive as they are inherently adaptive, where the security is achieved by adapting the communication rate and have low computational complexity as they are implemented with coding.

In particular, PLS could be used to enhance the resilience and robustness of IMT systems against active attacks at the physical layer through stealthy waveform and code design. In certain use cases, counter-jamming solutions such as a Faraday cage type of protection for smart factories can be very simple.

Keyless transmission of confidential messages is also possible. With the emergence of very narrow beamforming, wiretap coding can be used at mmWaves and sub-THz, irrespective of the

eavesdropper capabilities and position. Research on the secrecy guarantees at finite block lengths has allowed better understanding of the trade-off between secrecy rate, error rate and information leakage.

Finally, there is the ability to carry out anomaly detection at the physical layer. There are lightweight proposals for distributed anomaly detection by observing metrics such as transmission and reception times and energy and memory usage, and these could be used to protect radio interfaces of IMT towards 2030 and beyond.

6   Technologies to enhance the radio interface

6.1   Advanced modulation, coding and multiple access schemes

6.1.1   Advanced modulation schemes

Modulation is one aspect that can be revised in IMT towards 2030 and beyond. High-order quadrature amplitude modulation (QAM) constellations have been used to improve spectral efficiency in high signal-to-noise (SNR) situations. However, owing to the non-linearity of hardware, the benefits obtained in higher-order QAM constellations are gradually waning.

The high data rate communication capability of an IMT towards 2030 and beyond link transmission is expected to be improved by at least 10–100 times that of IMT-2020 to achieve 1 Tbit/s target. Radio implementations are typically limited in range of 10% relative bandwidth (BW) and thus this means that even in the upper mmWave region (100-300 GHz), a single RF transceiver can support only a 20-30 GHz bandwidth, subject to the linearity of RF components. A 1 Tbit/s of uncoded data requires 1 THz of bandwidth with binary modulation. Higher-order modulations with better spectral efficiency, the BW reduces in the range of 170 GHz for 64-QAM. This still seems very challenging, given that the highest RF bands under consideration for IMT-2020 usage are in the range of 100 GHz, and even the lower mmWave bands starting from around 24 GHz are just being ramped up commercially. It was proposed that the BW required for 1 Tbit/s communications needs to be split at least in six and preferably a larger number of parallel, not mutually interfering, orthogonal channels.

For example, new modulation methods, schemes based on signal shaping, have been adopted in other systems and have proved to be effective in optical fibre communication or broadcast system. Extended research is required for low peak-to-average-power-ratio (PAPR) modulation schemes with good performance to enable IoT with low-cost devices, edge coverage in THz communications, industrial-IoT applications with high reliability and so forth.

Although the receiver can compensate the most, the residual phase noise will still impact the performance. Therefore, a new modulation scheme with good suppressing phase noise capability is another critical technological direction in the THz band.

6.1.2   Advanced coding schemes

In addition to novel modulation and waveforms, new codes also need to be designed. Emerging applications require new channel coding schemes to address two requirements, i.e. extreme performance and diverse use cases. Extreme performance includes faster data rate, higher reliability, lower complexity and less power consumption. For example, high-fidelity AR/VR requires higher data rate than IMT-2020 channel codes. Autonomous driving requires end-to-end delay and reliability, asking for short code design approaching finite-length performance bound. More diverse demands mainly come from converged heterogeneous networks and machine type communications. These requirements, i.e. throughput (peak/guaranteed data rate), energy and cost efficiency, battery life, air interface delay, reliability and coverage among others, are summarized into a set of KPI-tuples that future channel coding schemes must tackle with.

The throughput of a single decoder in a future device will reach hundreds of Gbit/s. Infrastructure links are even more demanding since they aggregate user throughput in a given cell or virtual cell, which is expected to increase due to spatial multiplexing. However, it will be difficult to achieve such a high throughput, only relying on the progress of integrated circuit manufacturing technology within ten years. Solutions must be found on the algorithm side as well.

To further develop IMT technologies, the advanced coding schemes need to be investigated, including advanced versions of Polar Coding, Low Density Parity Check (LDPC) and other coding technologies. Owing to the diverse demands, the advanced codes should demonstrate superior performance over a wide range of code lengths and rates, support flexible choices of decoders and preferably unified into a single framework. To meet the higher throughput than legacy IMT systems, both code design and corresponding encoding/decoding algorithms need to be taken into account to reduce the decoding complexity and improve decoding parallelism. Besides, it is vital for a channel coding decoder to maintain a reasonable power consumption level. Considering the dramatically increased throughput requirement, the energy consumption per bit needs to be further reduced by at least $1 \sim 2$ orders of magnitude. It is also expected that some emerging scenarios such as new verticals and intelligent services may require novel coding schemes.

Application scenario-oriented designs need to be considered. For example, for the mixed scenario of "eMBB+URLLC", the design of forward error correction (FEC) code needs to consider "higher code rate (for higher data rate) + stronger error correction ability (for higher reliability) + lower error floor (for shorter latency due to reducing the number of hybrid automatic repeat request (HARQ) retransmissions)". In future high-reliability scenario channel coding schemes should provide lower 'error floor' and better 'waterfall' performance than that in IMT-2020. Short and moderate length codes with excellent performance need to be considered. Accordingly, at the BS side, depending on application scenarios and user device types, the adaptive switching between different FEC coding schemes or FEC coding scheme with different parametrisation is worthy of being considered.

In addition, new coding strategies should encompass both FEC and novel iterative re-transmission/feedback mechanisms. This is particularly the case for applications which require short packets, such as in IoT systems. LDPC codes and Polar codes that have short block lengths have been employed for IMT-2020 systems for use in traffic and control UL/DL channels. On one hand, codes with short block lengths are less reliable, such that error-free transmission cannot easily be guaranteed. An increase in the error probability may increase the need for automatic repeat request (ARQ) re-transmissions, which may not be suitable for time sensitive applications requiring ultra-low latencies. On the other hand, codes with longer block lengths also imply increasing latency. To this end, the interplay between the minimum required block length and robustness against transmission errors needs to be optimized. Furthermore, low energy applications are often not well suited to ARQ, since this requires leaving the device in a non-sleep mode for an extended period of time, leading to an increase in energy consumption.

6.1.3 Advanced waveforms

Over the past decade, OFDM has, by far, become the most dominant modulation format. It is being applied in the DL for both IMT-Advanced and IMT-2020. For some future applications, OFDM may still be retained due to backward compatibility. However, some effects of OFDM like sensitivity to frequency dispersion and high PAPR may become more critical at mmWave and THz frequencies. In addition, future IMT system will face unprecedented complex communication scenarios, where enhanced waveform design may be beneficial in specific scenarios to guarantee desirable performance. For example, in scenarios with high mobility or high frequency bands where the orthogonally between subcarriers will no longer be maintained. Also, in scenarios where low PAPR is needed, such as for low-cost devices or to reduce the impact to power amplifier in very high frequency band (e.g. sub-THz), new waveform design should also be investigated. DFT-s-OFDM is a variant of OFDM which provides low PAPR and is already used in current and previous IMT

systems and should therefore also be considered as baseline for low PAPR waveforms in future IMT systems.

Modulation methods can be classified under orthogonal, bi-orthogonal and non-orthogonal categories. Besides classical OFDM, other orthogonal techniques include null suffix OFDM, filtered multitone, universal filtered multicarrier (UFMC), lattice OFDM, Filter Bank OFDM and staggered multitone (FBMC). Among bi-orthogonal methods, there exists cyclic prefix OFDM, windowed OFDM, and Bi-orthogonal frequency-division multiplexing (FDM). For non-orthogonal schemes which need to eliminate inter-symbol interference via more complex receivers include generalized FDM (GFDM) and faster than-Nyquist signalling.

Historically, Doppler frequency shifts (or its dual time-varying effects) have long been considered as a type of degree of freedom to provide additional diversity gain. The transformed domain waveform design, i.e. orthogonal time frequency space (OTFS), is an effective approach to harvest the gain of Doppler domain diversity when the waveform can extend sufficiently in time to enable low enough Doppler resolution. Moreover, for high-speed scenarios, OFDM with advanced reference signals design also have the capability to track the time varying channel due to the Doppler effect. Thus, further enhancement based on OFDM waveform can also be investigated in future.

It is likely that for future IMT applications, OFDM may still be retained due to backward compatibility. Nonetheless, it has long been pointed out that OFDM has several drawbacks arising in non-ideal situations, which motivates further research into either modified multicarrier systems or other alternatives.

6.1.4   Multiple access

Multiple access technology is the key technology to enable a large number of users sharing the overall radio resources, which has been cornerstones for the evolution of wireless standards. It can increase the capacity of the system and allow different users to access the system simultaneously. Generally, from the way of resource sharing, multiple access can be classified as orthogonal multiple access (OMA) and non-orthogonal multiple access (NOMA), while from the access procedure, multiple access can be classified as grant-based multiple access and grant-free multiple access.

Orthogonal multiple access has been the longest adopted multiple access scheme from the earlier cellular communication system to IMT-2020. As an advanced form of FDMA, orthogonal frequency-division multiple access (OFDMA) scheme has been utilized in both IMT-Advanced and IMT-2020 systems. On the other hand, NOMA also allows multiple devices to share the same physical time and frequency resources, thereby efficiently connecting a large number of sporadically transmitting devices. However, the success of this approach primarily depends on both user detection and data decoding on the shared resources.

The requirements for future networks are very challenging, and the KPIs vary considerably from application to application. Multiple access techniques require a re-think in IMT towards 2030 and beyond, especially due to the integration of massive connectivity and extremely low energy applications. Current systems use contention access methods and/or non-contention access methods such as orthogonal time-frequency division multiple access for cellular systems. However, these multiple access schemes do not scale well to scenarios where thousands of devices or more aim to access a single BS, but with a low duty cycle.

Therefore, the new multiple access should be very dynamic and application oriented, for example, new structures that allow for better scaling and possibly further reduce latency. Different types of multiple access techniques should be used under a ubiquitous umbrella. There are several promising candidates for that.

The multiple access via massive-MIMO could be the one that has the strong potential. It can provide a very directive beam for each device to enable multiplexing with a very low inter-beam interference.

Despite associated drawbacks such as cost (e.g. RF chains) and complexity, the recent progress in massive-MIMO (e.g. holographic or lens antenna array) theoretically proves these challenges could be overcome. However, the massive-MIMO is not a one size fits all case. In fact a large number of antennas makes massive-MIMO unsuitable for specific scenarios (e.g. IoT applications). For these scenarios, there are other promising NOMA solutions such as Multi-User Shared Access (MUSA), Pattern Division Multiple Access (PDMA), sparse code multiple access (SCMA) and cyclic prefix code division multiple access (CP-CDMA), where each can provide very spectral efficient solutions to overcome the resource block bottleneck in sub-6 GHz.

For IMT towards 2030 and beyond, the usage of NOMA in diversified scenarios can be further investigated and identified to provide better performances. A fundamental rethink of the conventional multiple access technologies is required in favour of grant-free schemes suited for massive random access. The further development of NOMA is expected to meet future requirements including more massive connectivity, higher spectral efficiency, low latency and lower implementation complexity, and to provide differentiated service capabilities.

The evolution of NOMA should consider identifying the potential application scenarios that can reflect the NOMA gain and the evolution of NOMA technology itself. Depending on future requirements and the characteristics of NOMA technology, potential application scenarios that can reflect NOMA gain, particularly under massive connectivity should be identified. For example, in massive connectivity application scenario, more sequences need to be generated to support the simultaneous transmission of large numbers of terminals.

Besides above discussion of various multiple access schemes for resource sharing, from the access procedure, multiple access can be classified as grant-based multiple access and grant-free multiple access.

In grant-based multiple access, users (i.e. the transmitters) are coordinated by a central unit (i.e. an AP or a BS) prior to the transmissions and each user is assigned a unique signalling/signature which can be used by the receiver to perform detection. Grant-based multiple access requires dedicated multiple access protocols to coordinate the communication of the accessible users in the systems. Grant-based multiple access technology has become mature and been adopted by various wireless communication standards.

However, the grant-based multiple access technology, designed for current human-centric wireless networks, is not appropriate for future autonomous thing-centric wireless networks to support millions of devices in the future cellular network. On the other hand, Grant-free multiple access does not need to perform a sufficient coordination among the users, and can more efficiently handle the low latency requirement, scheduling information deficiency, or the bursty and random access pattern of user activity. Grant-free multiple access technology has been mainly used in the initial access, and several challenges must be overcome to realize grant-free multiple access. Challenges include the performance limits of massive bursty devices simultaneously transmitting short packets, the requirements of low complexity and energy-efficient coding and modulation schemes for massive access, and efficient detection methods for a small number of active users with sporadic transmission.

For example, it is reported that spectrally efficient URLLC multiple access, scheduling, and protocols need to be developed for broadband URLLC, and a grant-free based multiple access is required for massive URLLC. It is noted that 1) ultra-broadband transmission techniques utilizing new spectrum or antenna technology need to be considered; 2) spectrally efficient protocol, channelization, and scheduling need be further developed for guaranteeing URLLC QoS; and 3) multiple access schemes supporting both massive connectivity and ultra-low latency need to be developed.

Moreover, the collisions of multiple packets in the same slot are one of main challenges in NOMA research. To solve these collisions and support a grant-free transmission of high user loading, non-orthogonal physical layer design should be considered. NOMA has been well researched in grant-

based schemes. However, in grant-free transmissions, the global power control, resource allocation and configuration cannot be used, which poses a challenge to deal with inter-user interference (IUI). The one-dimension discrimination of power domain brought by the near-far effect of grant-free transmission is not enough to deal with severe IUI. Therefore, higher-dimension domains like code domain and spatial domain should be considered. In code domain grant-free schemes, the transmitters preconfigure or randomly select their non-orthogonal spread codes. At the receiver side, the codes are detected and used to alleviate IUI. The prior knowledge of the statistic properties of data (e.g. constellation shape), codebook, and CRC result should be fully utilized for advanced blind detection.

Compressed Sensing (CS)-Based Random Access has re-emerged as a signal processing technology for massive connectivity with grant-free or unsourced random access. A typical IoT network involves sporadic traffic patterns because only a small subset of devices is activated at any given time slot to minimize energy consumption. Considering that some active devices initially send their unique preambles (metadata) to the base station before directly transmitting the data signals, here, CS can be effectively applied to detect the active devices and estimate their channels from the metadata transmitted by IoT devices. It is also mentioned that grant-free or unsourced random access can reduce the signalling overhead at the expense of high computational complexity at the base station, as well as improve energy-efficiency.

6.2   Advanced antenna technologies

MIMO is a key air-interface technology underpinning nearly all wireless standards. Despite the great success of MIMO to date, there still exists a significant gap between the performance of MIMO systems in practice versus the information-theoretical capacity bounds. A key reason behind this trend relates to the challenge of dealing with the cost and complexity of large-scale antenna systems which has resulted in the use of lower-order MIMO with sub-optimal signal processing and procedures. Novel solutions and enhancements are therefore needed to bridge the gap between MIMO performances in practice versus theory, and to facilitate the operation of extremely large antenna arrays in future IMT systems.

As an advanced antenna technology, extreme MIMO (E-MIMO) is further development of massive MIMO, which is widely deployed in IMT-2020 systems. It can be achieved by exploiting much larger antenna array, using new materials, applying new deployments and new tools, offering new services, etc. The new deployments of E-MIMO include distributed deployments and AI technology is one of the most crucial new tools for E-MIMO. E-MIMO will be used to achieve better spectrum efficiency, larger network coverage, accurate positioning, accurate sensing, higher energy efficiency and so forth.

Wireless communication over mmWave or even higher frequency suffers from serious propagation loss and molecular absorption loss, which drastically limits the communication distance and coverage. The extreme high processing gain provided by E-MIMO is able to extend the communication distance and to realize superior data throughput and unprecedented user experience requirement for future wireless system.

The realization of E-MIMO depends on the development of antenna technology. With emerging technologies such as ultra-dense antenna technology and highly integrated RF chip, extreme large antenna array with high energy efficiency and realistic dimensions could be constructed. Accordingly, the number of antenna elements will be scaled up by a further order-of-magnitude for IMT systems towards 2030 and beyond. The significance of large-scale antenna systems is twofold. First, it increases the capacity and diversity of a MIMO transmission system. Secondly, it can support a large array gain to counter the extreme loss observed in millimetre waves and THz transmission systems from a beamforming perspective. The extension in the scale of antenna array offers narrow beams with extremely high spatial resolution and high processing gain. E-MIMO can be exploited to further

enhance multi-user transmission capabilities of network, which is crucial for improving spectral efficiency.

Lens antennas can be used to increase array gain. However, in practice, this may be difficult to achieve due to the presence of aberration and spill over losses. Antennas at sub-THz region will need to be tightly integrated with the packaging, RF circuits, and systems to optimise interconnections losses between radio transceivers and antennas and thus improve the radiated radio performance.

Future communication system with many antennas could also be built with multiple chips that each contains on-chip antennas in the same semiconducting substrate as the active circuitry on the chip. Nanotechnology opens new perspectives for THz communication to design and manufacture nanoscale electronic devices and systems in the terahertz range. Graphennas, i.e. graphene-based plasmonic nano-antennas, provide a technology to radiate electromagnetic waves with competitive conductivity over 100 GHz frequencies. Different kinds of metasurface can be added as part of the antenna structure for improving the antenna gain, isolation, reflectivity, or other properties.

Besides the extension in scales of antenna array, new types of antenna arrays can be applied for better performance, various array sizes, low cost or more convenient deployment. The new types of antenna array involve various types of reconfigurable antenna arrays, passive/active antenna arrays with new RF architectures, and antenna arrays with new materials, spatially continuous transceiver aperture and so on.

As the performance of E-MIMO will ultimately be limited by the propagation channels, the propagation channel is also a vital topic. As the number of antenna elements is increased, the total physical aperture of the radiating elements is also increased, and effects such as wavefront curvature due to scattering in the near field of the array, shadowing differences in different parts of the array, and beam squinting due to the non-negligible run time of the signal across the array, start to become much more pronounced. When this happens, conventional propagation theories and results exploiting the plane wave assumption start to breakdown. All of these physical artifacts need to be taken into account in the design and implementation of beamforming architectures and signal processing algorithms at the transmitter and receiver.

Ideally, E-MIMO should be implemented using fully digital arrays with hundreds or thousands of phase-synchronized antennas. While this could be practically possible in both sub-6 GHz and mmWave bands, the implementation complexity grows with the carrier frequency. For some IMT-2020 deployments, digital beamforming remains the choice of interest, due to its ability to provide a higher beamforming gain, while utilizing the channel's spatial degrees-of-freedom. In sharp contrast, most current commercial deployments at mmWave frequencies use analogue beamforming to explicitly steer the array gain in desired directions. This is since digital beamforming at mmWave frequencies yields high circuit complexity, energy consumption and cost of operation. In the future, closer investigations of fully digital implementations at mmWave frequencies are merited. For instance, new device technologies, potentially leveraging new materials, can be utilized to implement on-chip compact ultra-massive antenna arrays that can potentially enable fully digital architectures. New implementation concepts are needed that do not involve the suboptimal beam-space paradigm, as in the case of hybrid beamforming, but can make use of all the spatial dimensions. In addition, the compromise solution of hybrid beamforming striking the right balance between processing in the analogue and digital domains has also received considerable attention.

With optimal beamforming architecture, E-MIMO provides extremely high spatial resolution. It is capable of achieving very high positioning accuracy with E-MIMO. By equipping antenna array at both sides of a communication link, orientation of user device could be obtained with 3D positioning. Furthermore, at THz frequency band, highly directional pencil-like antennas enable sensing applications capable of creating high-definition images of the environment and surrounding objects. In fact, such high-resolution scanning in the beam space domain has the potential to create real-time detailed 3D maps; thus, enabling elaborated digital twin applications in industrial use cases, or

innovative sensing applications capable of implementing touchless interfaces by tracking gestures. Alternatively, this high-resolution beamspace processing when used along with location information can also support proactive resource allocation/management in future communication systems.

Algorithms which provide the right balance between run-time complexity, ease of real-time implementation and optimality in performance need to be investigated such as spatial modulation, a lower complexity alternative to traditional multiple antenna methods, holographic beamforming and the use of meta-materials. Various aspects of such methods are investigated for channel estimation, differential implementation, and hybrid methods.

Yet another dimension of E-MIMO involves the signalling protocol to enable operation of large antenna arrays. To prevent an excessive increase in signalling associated to the CSI for MIMO transmission and beam management, and to assure a high overall spectrum efficiency, introduction of advanced CSI mechanisms is an essential element of future E-MIMO systems.

6.2.1 E-MIMO with new type of antenna arrays

It is well known that increasing the number of antennas results in monotonic increase in MIMO capacity. Moreover, the use of higher frequency bands such as THz in future IMT system requires ultra-massive antenna arrays to deal with the propagation loss. However, there are fundamental challenges such as increased cost and weight, which limit the number of antennas that can be packed onto conventional arrays.

A potential remedy to increasing the number of antennas lies in integrating a considerably large number of passive reflective elements onto surfaces with electronically steerable RF operation, known as holographic MIMO. Theoretically, this concept can provide advanced beamforming and spatial-multiplexing capabilities at very low costs (e.g. with software-controlled metasurfaces). Such reflect arrays can also be used enhance coverage performance in existing MIMO deployments. However, there are many open challenges associated with its practical implementation, such as channel estimation and reconfiguration issues. In short, tools from AI/ML are likely to play a key role in tackling some of these open problems on holographic MIMO.

6.2.2 E-MIMO with distributed mechanism

Increased spectral efficiency by E-MIMO systems and advantages of distributed IMT systems are being well understood in theory. Distributed E-MIMO is a technology that combines the advantages of both E-MIMO technology and a distributed system. The TRxP (Transmission and Reception Point) in distributed E-MIMO can be distributed over a substantially larger area and coordinated to expand coverage and improve spectral efficiency, particularly for cell-edge users. The TRxPs could also be reached via wireless backhaul in the forms of relay. Distributed E-MIMO can reduce power consumption by moving the network closer to users, and its networks can effectively reduce interference and eliminate the user's sense of boundary through intelligent interaction and collaboration between different base stations.

Compared to the distributed systems in IMT-2020, distributed E-MIMO system involves more cooperation TRxPs, new types of distributed TRxPs and new types of system architectures. The term 'cell-less' (or 'cell-free') refers to the fact that the network appears to be without any cell boundaries during data DL transmissions, at least from a user perspective. The data detection on the UL can be performed at each BS, at the central processing unit (CPU) or the detection can be split between the BS and the CPU. The network might not be cell-free for control signals as BS specific synchronization and reference signals might be used.

Cell-free E-MIMO is a type of distributed E-MIMO that can effectively reduce interference and eliminate the user's sense of boundary. As a user-centric network, cell-free E-MIMO involves a novel network architecture, new access technology and so forth. The network is user-centric, meaning that each user is connected to a user specific subset of BSs that jointly serve the user. The BSs are

connected via front-haul connections to CPUs that coordinate transmissions from BSs phase-coherently, and the CPUs are inter-connected via backhaul connections. In case Time division duplex (TDD) is used to ensure scalability in massive MIMO systems, channel estimation and precoding can be performed by each BS according to channel reciprocity. Therefore, no instantaneous CSI needs to be sent over the fronthaul.

A new type of distributed TRxP is a transparent forward TRxP with limited processing capability that its beamforming parameters are controlled by a BS or a CPU. Such TRxP may also use RIS as its transmission/reception antennas. It is different to traditional relay based distributed MIMO system since signals can be reflected/ transmitted directly and full duplex can be realized at the TRxP. For a distributed E-MIMO system with such new type of TRxP, designs of following factors can be taken into consideration: the interface between the distributed TRxP and BS/CPU, channel model, synchronization, interference coordination and others.

One of the main challenges for implementing cell-free massive E-MIMO networks are to have cost efficient deployments while achieving sufficiently accurate network synchronization and satisfying the requirements for the fronthaul and backhaul connections. Another challenge is to realize promised theoretical gains in practice for realistic scenarios with distances spanning up to hundreds of metres and variations in UE/scatter mobility. Moreover, since UEs in cell-free E-MIMO networks can communicate with multiple access points at the same time, practical factors such as channel information acquisition, RF channel calibration, synchronization, precoding algorithm, etc. should be considered.

6.2.3 E-MIMO with AI assistance

Tools from AI/ML are particularly suited for dealing with the inherent complexities of E-MIMO operation. In addition to enabling solutions towards dealing with various sources of RF impairments in MIMO transceivers, such as power amplifier non-linearities, the adoption of AI-based techniques to replace conventional signal processing blocks, such as channel estimation and detection can lead to performance improvements and/or complexity reduction in the short and medium terms.

AI-based techniques can be used effectively to continuously match reference signal density to channel variation, compress CSI feedback by accurate prediction, and reduce beam-pairing complexity. In a MIMO environment where there are relatively many optimization factors, including the practical limitations of an ADC and RF chain, there are several efforts that send and receive a large amount of information with low transmission power. The encoder and decoder responsible for compressing and decoding information are viewed as a single deep neural network, both learning simultaneously. Combined with compressive sensing, compressing CSI can be implemented through DL. However, a metric such as mean-squared error can be used to evaluate image compression performance. Therefore, it is important to examine the communication metric.

Another representative example of solving a future IMT-system problem through AI is the beam selection problem. In millimetre waves, beamforming technology is essential owing to its relatively high propagation loss. The beam selection problem refers to selecting one of several beams stored in the BS. Instead of performing a full search of beams in all directions, the goal is to reduce the complexity of the search using AI. Studies have been attempting to solve this problem through AI, particularly with a DL -based method. However, the selection/provision of training data is the primary issue for handling the beam selection problem with AI.

And AI technology also can be used to assist RIS-based E-MIMO to realize the intelligent reconstruction of the wireless communication environment. In this way, network coverage, multi-user capacity and signal strength are enhanced.

6.3   In-band full duplex communications

The contradiction between the explosive growth of wireless communication traffic and the shortage of spectrum resources is driving the evolutions of wireless communication theory and technologies. Enhancing the spectrum efficiencies of Frequency Division Duplex (FDD) and TDD systems as well as eliminating the differences in both usage and management of the spectrum resources has become one of the goals for technology innovations in future mobile communications. The research on self-interference cancellation (SIC) technology and its applications makes it possible to further realize the practical requirements such as in-band Full Duplex communications, reducing the FDD guard band and suppressing the interference between co-located heterogeneous systems.

In conventional communication systems, DL and UL transmissions occur mutually exclusively either in time domain (i.e. TDD) or in frequency domain (i.e. FDD). Generally, in practical systems, the DL and UL receive fixed allocations of time-frequency resources. Dynamic TDD was introduced in IMT-2020 system to enhance the duplex flexibility, thus facilitating adjustment of the ratio between DL and UL time slots depending on traffic demand. While this is an improvement over earlier IMT systems, there is still active study on how to remove the restriction that DL, and UL must use mutually exclusive time-frequency resources. Hereafter, this restriction is referred to as the 'mutually exclusive' principle.

In theory, allowing an overlap between DL and UL over the entire time-frequency resource (or 'full duplex') can increase the system capacity twice. Self-interference and cross-link interference are the main obstacles encountered upon deviating from the 'mutually exclusive' principle. Self-interference is experienced by a BS receiver when the BS transmits DL signal uses the same time-frequency resource used for the UL signal from UEs. Since the BS transmit and receive antennas of a BS are located in close proximity, self-interference is much stronger than the desired signals from the mobile device. Therefore, it is crucial to be able to remove self-interference to evolve duplex technology by departing from the 'mutually exclusive' principle. There has been related research on SIC techniques, which typically require both analogue and digital domain cancellation.

Cross-link interference (CLI) refers to the interference between UEs or between BSs. For example, UEs maintain the 'mutually exclusive' principle between its transmission in UL and reception in DL whereas BS does not. CLI between UEs is caused if the same time-frequency resource is allocated for the UL transmission from a UE and the DL transmission to another UE. The UE-to-UE CLI can be mitigated if a BS chooses a set of UEs that do not cause severe interference to each other. The CLI between BSs occurs when the aggressor BS's DL uses the same time-frequency resource as the victim BS's UL. Close coordination between BSs can mitigate BS-to-BS CLI.

From the perspective of SIC applications, the standalone full-duplex radio with low-power and small-scale antennas has readily applied SIC technologies in practice. In relay and backhaul scenarios, full-duplex equipment with SIC capabilities has also been partially deployed. Whereas in massive MIMO full-duplex networks, the inter-cell interference cancellation and the SIC for large-scale antennas still need breakthrough. From the perspective of SIC devices and components, the breakthrough of miniaturized high-isolation antennas will significantly improve the SIC capability, and the realization of variable delay chips with wide programmable ranges required by RF SIC technologies will significantly promote the research on high-power SIC innovations. While from the perspective of SIC signal processing, the cancellation of nonlinear SI components originated from the power amplifiers in massive MIMO systems is still quite challenging at present. Meanwhile, the convergence time and robustness of current RF SIC will further limit the performance gain of the whole link under rapidly-varying channel environments. Full duplex networking will cause more complex cross-link interference, including the UE-to-UE and BS-to-BS interference. Advanced interference measurement and management mechanisms are needed to exploit the benefit of full duplex in networking.

In today's practical cellular systems, a band has a fixed duplex scheme, i.e. either FDD or TDD. If deviating from the 'mutually exclusive' principle becomes a reality, it would be possible to adapt the duplex scheme in a dynamic manner. This would improve the spectral efficiency as well as the system operation flexibility

There are significant challenges to vary the duplex scheme on existing links. Research into the gains of sub band duplex will help identify the gains and the feasibility of full duplex under different interference scenarios.

6.4 Multiple physical dimension transmission

Spectrum resources are scarce, particularly in the sub-6 GHz bands that define the baseline coverage of a network. Hence, achieving full utilization of the spatial dimensions (i.e. how to divide the available spatial resources between concurrent transmissions) is particularly significant. Novel techniques such as reconfigurable intelligent surface (RIS), Holographic radio (HR) and Orbital angular momentum (OAM), are potential technologies to improve the performance and overcome the challenges in traditional beam-space antenna array beamforming.

6.4.1 Reconfigurable intelligent surface

Traditionally, the propagation environment between a transmitter and receiver has been perceived as a non-controllable component of wireless systems. However, RIS is fast emerging as a key wireless technology trend for beyond IMT-2020 systems, where it enables dynamic control over the radio environment by adapting the channel parameters such as phase, amplitude, frequency, and polarization through tuneable scatterings of electromagnetic waves. More specifically, as a new type of antenna array with or without active elements used in a transceiver and/or a relay, RISs use many small sub-wavelength unit-cells whose individual reflection, refraction, and absorption properties can be controlled to construct an intelligent and programmable radio environment. Moreover, highly energy-efficient communication can be achieved as it operates without complicated decoding, encoding, or RF operations.

RIS may be implemented using mostly passive components without requiring high-cost active components such as power amplifiers and ADCs and DACs resulting in low implementation cost and energy consumption. Moreover, it lowers deployment costs, thereby refining the feasibility of large-area deployments. Being almost passive, RIS is unlikely to increase exposure to electromagnetic fields. Besides, RIS can support higher spatial resolution over traditional antenna arrays since electromagnetic waves can be reconstructed at any point on their continuous surface. Owing to their ability to take any shape, they can adapt to different application scenarios and be integrated with existing objects (e.g. walls, buildings, lamp posts).

Orders-of-magnitude higher spectral efficiencies may be achieved via the introduction of RIS when operating passively. The spectrum efficiency gains are not realisable for microwave channels that are operating in full rank. Additionally active surfaces could be considered but this will be comparable to deploying newer BS sites. Systems operating in the 24-71 GHz bands or in bands > 100 GHz, IRSs/RISs can increase the overall channel rank by creating alternative paths for the transmitted waveform.

RIS makes it possible to intelligently control the propagation environment, improve transmission reliability and achieve higher spectrum efficiency. RIS can be applicable to the following scenarios:

– Facilitate increasing the channel rank to achieve the full multiplexing gain in NLOS scenarios, which can support the hot-spot area and boost the cell-capacity

– Expand network coverage including outdoor DL coverage and UL enhancement, outdoor-to-indoor coverage, and airline coverage

– Improve cell-edge performance, and help mitigate multi-cell co-channel interference

–   Phased antenna arrays using only a single RF-input for each array and a programmable distribution network to vary dynamically the directivity of the beamforming, enabling ultra-massive MIMO (thousands of elements) at low cost and low power

–   Improve positioning and sensing performance

–   Wireless power transfer and backscattering to relieve energy consumption for battery-powered devices.

For RISs to be ready for successful commercial deployment, several open research challenges need to be addressed, including:

–   development of accurate device electromagnetic models and channel models and their experimental validation

–   studying the fundamental limitations and potential gains of RIS-aided communication systems and thereby identifying scenarios where deploying RIS offers advantages over traditional relays and non-reconfigurable passive reflective structures

–   passive beamforming design

–   new channel estimation is required due to lack of an RF chain

–   materials research and studying on hardware implementation issues

–   real-time control protocols for RISs

–   there are enormous challenges with integration of the active IRSs/RISs to the core network, since a dedicated link for control signalling between BSs and IRSs/RISs presents itself as an addition to the existing transport network of unspecified bandwidth and a consequential increase in the control plane latency

–   the bandwidth of the transport links to the RIS would depend on the number of elements at the RIS/IRS, the number of control bits per-elements, their refresh rates, and the data frame transmission time intervals and would also scale with the number of UEs. Consequently, the number of surfaces per sector/cell remains unclear

–   the transport links would also have an impact on the network architecture that needs to be analysed

–   the vulnerability of the surface elements due to inclement weather would. Lead to pixel failures.

RISs turn the wireless environment from a passive to an intelligent actor, so the channel becomes programmable. Importantly, it is characterized by low cost, low power consumption, and easy deployment. So, this new fundamental technology will challenge basic wireless system design paradigms, create innovation opportunities which may progressively impact the evolution of wireless system architecture, access technologies, and networking protocols over the next decade.

6.4.2   Holographic radio

Holographic radio (HR) can be applied in the use cases, such as high-precision positioning and perception, smart factory and immersive media. It utilizes the spatially continuous electromagnetic aperture and interference exploitation to enable spatial multiplexing and spectral multiplexing with pixelated ultra-high resolution. Comparing the beam-space approach, HR has native intelligence because it models refined holographic electromagnetic space by Fresnel-Fraunhofer interference, diffraction, and spatial correlation modules, which is similar to the deep neural network. HR can upgrade RF holography to optical holography and, by doing this, optical signal processing schemes like time inversion and aperture coding coherence can replace the traditional equalizer. Hence, HR can make use of all available spatial dimensions to achieve benefits in terms of flexibility, spectral efficiency, delay, power consumption and complexity. HR has been studied to some extent in the fields of RF holography with ultra-high resolution, but the application in the field of wireless

communication still faces many challenges including integration between microwave photonics-based continuous aperture active antenna array and high-performance optical computing, hardware design and physical layer design issues.

6.4.3 Orbital angular momentum

OAM imposes 'twists' on the phases of the propagating laser beams, such that modes with different amounts of twist are orthogonal to each other. Studies have focused on its beams and advanced transceiver designs as potential solutions to increase the spectral efficiency of line-of-sight (LOS) propagation or reduce the hardware complexity of extremely high data rate in future IMT systems. OAM in air-interface accessing application between BS and UEs face more challenges to directly obtain multiplexing gains of different OAM modes. Investigations on how to make such systems robust to practical impairments of multipath, misalignment of orientation, etc., are critical to improve their practical utility. While some preliminary work has been completed in that direction, e.g. in multipath propagation and turbulence, extensive studies are required to establish feasible systems.

Since OAM system or OAM-MIMO symbiotic system performs better with electrically smaller antennas and quasi-static terminal, it is much more suitable for indoor small cells with millimetre waves and THz systems, and in particular for free-space optics applications. Given the breadth of applications anticipated for future IMT systems, OAM solution may comprise three phases: i) vortex waveforms carrying OAM used as a set of beamforming patterns based on the universal antenna array of the MIMO system; ii) vortex waveforms carrying OAM used as multiple orthogonal sub-channels based on the dedicated antenna array of OAM system; iii) light photon of microwave photon carrying quantum state OAM used as a novel signal carrier. Depending on the maturity of technology, different phases of an OAM-based solution can be progressively introduced into future IMT systems.

6.5 THz communications

IMT systems for 2030 and beyond is expected to provide ubiquitous high-speed Internet access as an extension to optical fibre. Either holographic vision or future XR utilizing 6 degrees of freedom will require immense bandwidth up to several THz. Furthermore, from the perspective of backhaul network infrastructures, an increasing number of mobile and fixed users in the private and industry sectors will require hundreds of giga bits per second (Gbit/s) for connectivity to or between cell towers and remote radio heads. Fundamentally, there are three strategies to increase data rates: securing bandwidth, improving spectrum efficiency, and densifying networks. Since spectrum resources above 100 GHz are sparsely used, there is potential for new services and applications to make use of the spectrum above 100 GHz. Therefore, studies may be required on sub-THz and THz frequency resources, ranging from around 100 GHz to 3 THz to secure sufficient bandwidth.

As one of the possibilities to meet the requirements for future IMT systems, THz communications have been envisioned as key enablers for many future use cases. For example, the use cases requiring extremely high-data-rate, low latency, high-resolution sensing and imaging, and high-precision positioning enabled in the future IMT systems are important application scenarios in THz communications. Take extremely high-data-rate communications as an example, primarily due to vast amount of available spectrum at higher frequencies. Benefiting from the sufficient spectrum resources, THz band can provide ultra-high data rates from hundreds of gigabits per second (Gbit/s) to several Tbit/s. This can enable new applications such as holographic connectivity, communications with untethered multimodal extended reality goggles where viewport rendering is done at the network edge, intra-device communication, hotspot downloading, wireless connections within data centres, fixed wireless access and wireless cellular fronthaul/backhaul, some are as introduced in Reports ITU-R F.2416 and ITU-R M.2417.

As the combination of the above capabilities, THz communications can play a key role is in the further evolution of the concept of Digital Twin (DT). A DT is a virtualized real-time representation of a

physical asset including a representation of the asset's structure, role, and behaviour within the digital domain. In future this technology is expected to include representation of the environment as well and interactions between DTs, that require the transfer of vast information volumes, low delays and high reliability that can be enabled by THz communications. Moreover, mapping of the physical world to the digital world with extreme precision is made possible because of the precise positioning capabilities of THz/sub-THz systems due to their use of extremely fine beams and wide channel bandwidths. As an additional use case, future MR systems will allow humans to seamlessly interact with each other, and with physical and digital things, thereby enabling massive new capabilities in both work and social interaction. Again, this requires support for extremely high data rates, low latency, and highly precise positioning, which can be supported by THz communications.

It is evident from the wide-ranging applications that THz communications is an umbrella technology that contains multiple sub-systems and enabling use-cases targeting next generation IMT systems. Naturally, each sub-system will have its own detailed requirements. However, as in all commercially successful technology solutions, each of these sub-systems will need to deliver feasible size, weight, power and cost (SWaP-C) KPIs, which ideally satisfy the demand of the corresponding next generation of use-cases. An important KPI for the radio receiver (transmitter) is the energy expended per received (transmitted) bit of information.

On the other hand, there are some well-known challenges for the deployment of Tera-Hertz high frequency bands in IMT systems, e.g. high propagation loss with increased frequency, atmospheric/precipitation/foliage loss due to physical interaction of electromagnetic waves and the medium through which these waves propagate. In addition, THz signals are more vulnerable to different types of obstacles (e.g. people, walls, vehicles). The potential of THz technologies to shape the future of wireless communications is very much dependent on the ability to devise feasible enablers in terms of baseband processing, RF frontend and antenna design, propagation and channel modelling, beamforming and (ultra-massive) MIMO, as well as resource management and medium access control schemes.

6.5.1   Pencil-beam THz radio

Wireless connectivity in the THz regime creates the need for high-gain large antenna arrays with pencil-beam characteristics to cope with the high molecular absorption loss of the THz band. Narrow beams below ten degrees are already used in IMT-2020 millimetre wave communication systems to overcome increased signal path loss compared to the sub-6 GHz communication. Such communication is implemented with phase arrays at both ends of the communication link, and an identical approach can be adopted with IMT systems for 2030 and beyond. Such narrow signals are called pencil beams, which are steered with electrical beam steering by controlling the phases of the communication signals at both ends of the radio link. Owing to the extremely short wavelength at THz bands, the ultra-massive MIMO structure can be integrated within a small size, to provide high beam gain with flexibility in spatial signal pre-processing. Besides providing coverage extension by pencil-beamforming, due to the extremely short wavelength of THz spectrum, antenna elements become much smaller than those designed at millimetre wave bands and many more antenna elements can be integrated in the footprint. This ultra-massive MIMO system also improves spectrum efficiency by exploiting higher spatial resolution and frequency reuse.

High-gain directional antennas communicating over distances far beyond a few centimetres in the THz band require advanced beamforming techniques that are significantly affected by THz channel dynamics.

At first, the design of suitable pencil-beamforming algorithms to address the challenges of the THz band, with respect to number of antenna elements, calibration requirements, suitable frequency windows and others, is expected to play a key role in the next generation wireless technologies. These

algorithms will be focused on efficient device tracking in THz band by capitalizing on accurate channel models, efficiently designed signalling and optimized RIS design.

Secondly, THz technology also requires very directional antennas with ideally steerable features with beamforming capabilities. The complexity and losses associated with the antenna feed network may be challenging. Alternatively, the use of high gain, e.g. hemispherical lens antennas fed by a planar array with a moderate number of antenna elements may be attractive. Alternatives that are expected to advance further and reach to practical implementation level include Graphene based plasmonic antennas compatible in nano scale, plasmonic patch antennas, and Graphene based patch antenna array in Yagi-Uda MIMO configuration with beam-steering capabilities.

Thirdly, micro- and macro-mobility are critically important for THz wireless links to be practical part of an access system. This is especially true in mobile access cases while less so for backhaul connection. Even when a user is not moving it is highly possible for a mobile device to be rotated or moved with moderate speed over short distance due to the user's hand or other movements. It can also happen that blockage of the Line-of-Sight link may occur. In this case, device tracking may need to search for, e.g., a reflected path between receiver and transmitter provided by a RIS.

Furthermore, beyond the PHY layer, new link and network layer strategies for ultra-directional THz links are needed. Indeed, the necessity for very highly directional antennas (or antenna arrays) simultaneously at the transmitter and at the receiver to close a link introduces many challenges and requires a revision of common channel access strategies, cell and user discovery, and even relaying and collaborative networks. For example, receiver-initiated channel access policies based on polling from the receiver, as opposed to transmitter-led channel contention, are emerging.

Similarly, innovative strategies that leverage the full antenna radiation pattern to expedite the neighbour discovery process have been experimentally demonstrated. All these aspects become more challenging for some of the specific use cases.

6.5.2 THz transceiver technologies

To achieve Tbit/s transmission, a true THz communication system comprising all the necessary components, from antenna and RF components, through AD/DA conversion to digital signal processing, need to utilize the state-of-the-art components and it will be a significant challenge to tackle by 2030 and beyond. There will be paramount challenges related to cost, power consumption, and engineering resources required to solve all relevant open technical details.

To guarantee the implementation of THz communications in the IMT systems three areas of technology developments are required: transceiver architecture, RF device and baseband signal processing.

Transceiver architecture

To bring THz communications to fruition, several key pieces of the entire communication chain will have to be realized for successful commercial deployments. An important question relates to the transceiver architecture. In general, there are three kinds of transceiver architectures in THz communication systems that are widely developed, including solid-state based THz system, direct modulation-based THz system, and photoelectric combination-based THz system. Furthermore, the solid-state based THz transceivers fall into two broad categories, fundamentally operated and sub-harmonically operated transceiver architectures. Each of these approaches has its own merits and can better adapt to different requirements of the THz technology, such as high frequency capability of photonics and higher power output of solid-state based solutions. For next generation wireless systems, it is expected that these options will find their use and deployments for different scenarios and applications.

Receiver architectures will need to address the design of tuneable band filters, wideband low noise amplifiers, linear mixers and high-speed ADCs. Research will need to address the receiver architecture and support greater frequency agility. Also, integrated silicon and photonic devices are expected to play an increasing role in the signal processing chain in order to realise large bandwidths and high sampling rates. Technologies such as nano-opto-electro-systems, which support all silicon fabrication, are expected to make a significant contribution to the realisation of cost effective, low power Tbit/s modems.

Radio frequency (RF) devices

Another critical area for THz communications is RF and mixed-signal devices. The challenges here include lack of underlying analytical hardware models, design of high efficiency components including frequency conversion circuits, mixers, multipliers, power amplifiers (PA) and oscillators. Both the peak output power and power added efficiency of the THz PA and phase noise of the THz oscillators will be design challenges. Given that THz communication systems will likely utilize wide communication bandwidths, design of energy-efficient ADCs and DACs converters will also be a challenge.

While the THz-band channel supports bandwidth in excess of 100 GHz, the sampling frequency of state of-the-art DACs and ADCs is in the order of 100 Giga samples-per-second.

Operating at such high frequencies puts stringent requirements on the semiconductor technology. Since THz band is known as 'THz gap', two technologies such as electronics and photonics have been studied to develop THz transceivers. While the electronic technologies using silicon metal oxide semiconductor field effect transistor (MOSFET) transistors are predicted to have reached their peak speed, and will actually degrade with further scaling, silicon germanium (SiGe) bipolar transistors are predicted to reach a maximum frequency of close to 2 THz within a 5 nm unit cell. In such a technology, amplifiers and oscillators up to about 1 THz could be realized with high performance and integration. A better option may then be to use GaAs (Gallium Arsenide) or indium phosphide (InP) technology for the highest frequency parts, combined with a silicon complementary metal oxide semiconductor driven baseband circuit.

As an alternative of electronic technologies, two-terminal devices such as Resonant Tunnelling Diode (RTD) and Schottky-Barrier Diode (SBD) have been investigated for THz oscillation and detection functions, respectively. THz transmission experiment using those devices integrated with planar antennas has been demonstrated in the frequency up to 1 THz. Compact THz transceivers could also be developed using two-terminal devices because of the simplified structure compared with three-terminal devices and compatibility with planar antenna elements.

Photonics can extend the oscillation frequency by combination of $LiNbO_3$ (LN) single-sideband (SSB) optical modulators and uni-travelling carrier photodiode (UTC-PD). Regardless of complex configuration of photonic architecture, such technologies could be expected to deploy distributed antenna systems in limited areas such as indoor facilities. In addition to signal distribution through optical fibre in limited areas, the beam direction of the distributed antenna system can also be controlled remotely by assigning a wavelength to each beam at the so-called central station. This technology is expected to connect a large number of miniaturized and cost-effective remote BSs for future IMT systems.

Baseband signal processing

Another key building block of THz technology is the digital baseband component. Since THz system needs to deal with Tbit/s data rate, the baseband signal processing schemes for THz communications are expected to be low complexity and low power consumption. In particular, for the ultra-high-throughput use-cases, baseband solutions that are scalable in terms of data rates, power, and form factor will be instrumental for the future IMT system operating in THz frequencies.

While a wide bandwidth of tens to hundreds of GHz is expected to be used to achieve Tbit/s transmission, the ADC resolution is inevitably limited. Thus, baseband signal processing needs to be robust and energy efficient, adapt new bands' channel characteristics and new transmission schemes. New waveforms, channel coding, modulation schemes and antenna technologies are currently under study and development.

The realization of the ultra-fast, reliable and low complexity decoder with Tbit/s throughput is a key issue. There have been numerous efforts towards extending the range of the state-of-the-art design in terms of throughput. Although over 500 Gbit/s decoders have been implemented once for polar codes and LDPC codes, those designs were provided with limited code flexibility and performance compromise. Since channel coding is the most computationally demanding component of the baseband chain, efficient coding schemes need to be developed for Tbit/s operations. Nevertheless, the complete chain should be efficient and parallelizable. Therefore, algorithm and architecture co-optimization of channel estimation, channel coding, and data detection is required.

In contrast with sub-6 GHz systems, waveforms and modulation schemes will have to be co-designed with the sub-THz radio front-end to meet the required KPIs (e.g. energy/bit). Energy-efficient radio access technologies exploiting multiple degrees of freedom (e.g. spatial, spectral, and temporal) will have to be developed. New waveforms and a mix of analogue and digital (de)-modulation schemes will have to be developed to achieve state of the art energy/bit transmission efficiency. For example, to keep the modem complexity and power consumption low, solutions based on amplitude and phase-shift keying (APSK), which has a low PAPR, are attractive. The choice of multiple-access (MA) scheme will be strongly influenced by the implementation technology adopted. Therefore, different MA schemes need to be researched such as GFDM, Filter Bank Multi-Carrier (FBMC) and UFMC as well as schemes based on CDMA such as CP-CDMA or sparse sequence MA. And the increasingly sparse nature of the wireless channel in sub-THz frequency bands and the huge bandwidths of Tbit/s modems (e.g. >100 GHz) will have a major role in determining the optimal waveform, which may include joint functionality such as sensing as well as communication.

Joint channel estimation and detection, joint demodulation, and decoding are considered for low complexity and latency implementation. For Tbit/s channel coding, code design and decoding algorithms are also expected to be developed regarding parallelizability, implementation constraints, and new channel characteristics. Newly coded modulation schemes can be combined for better spectral efficiency, and deep-learning aided approaches can also be applied commonly to both baseband signal processing and channel coding algorithms.

In addition, the baseband complexity can further be reduced by using low-resolution digital-to-analogue conversion systems, and all-analogue solutions should also be considered.

For a practical Tbit/s baseband modem, low complexity, high-parallelized systems and efficient signal processing algorithms for THz MIMO systems are expected to be developed.

Related with beam forming, Classical MIMO has several limitations, and specifically, the complex DSP implementation will be a major drawback compared to an RF/analogue beamforming approach. Even then, the required parallelism and complexity of combining signals from different antennas and steer beams goes well beyond what has been seen in any communications or radar system below 100 GHz. Circular polarization diversity MIMO is yet another way to overcome these channel bandwidth limitations. Physical and financial constraints are setting strict boundaries, and as the continuum of Moore's law requires the favourable and rapid development of core technologies from semiconductor processes to complete chipsets and other associated components like antennas to keep the past trend moving forward to enable Tbit/s communication modem implementation at the base and mobile stations. A significant improvement of signal processing power with reduced power consumption compared with current IMT-2020 mobile station implementations is needed to enable one Tbit/s communication modem.

6.5.3   Spectrum aspects for THz

The spectrum from around 100 GHz to 1 THz may be considered for IMT systems for 2030 and beyond. Critical advantages of THz band include: 1) wide potentially available portions; 2) the ability to develop ultra-massive MIMO antenna arrays within a reasonable form factor; and 3) the ability to support ultra-high bandwidth applications.

Moving to new frequency bands usually entails determination of the fundamental propagation processes. It is vital to establish the accurate channel models that characterise the pathloss and frequency selectivity of THz channels, leading to maximize the bandwidth allocation and improve the spectral efficiency. Since there is no channel model in THz band yet, the IMT-2020 channel model in Report ITU-R M.2412, which is applicable for up to 100 GHz, may be developed to THz band. Detailed channel models for various sub-THz frequency bands (e.g. 110 GHz, 140 GHz, 220 GHz and 300 GHz) will have to be generated for various use cases and deployment scenarios (e.g. in-door gaming). Both spreading loss and absorption loss will need to be carefully modelled.

Atmospheric attenuation in the THz bands is much higher than the mmWave bands. The efficiency of diffraction is greatly reduced at mmWave and even more at THz frequencies. A lot more work is required to improve the lack of models for both high mmWaves and THz channels, with the main challenges being as follows: 1) design and construction of suitable measurement equipment; 2) a mixed deterministic-stochastic modelling approach is required; 3) in order to characterize the stochastic part of the model, extensive measurements are required, which are currently missing, pointing to the large open gaps at THz frequencies.

6.6   Technologies to support ultra-high accuracy positioning

The positioning information of an object such as its location, speed, and direction can be used for safety and productivity improvement. This information would be applied to services requiring real-time data and high accuracy, which include unmanned aerial vehicle operations, augmented reality, movement of mobile trolleys in smart factories, and traffic monitoring and control. Millimetre-level accurate positioning is possible when using the satellites with the aid of real-time kinematic techniques. However, it is difficult to provide positioning services through satellites in dense urban or indoor areas where satellite signals are difficult to reach. When using communication radio waves such as the current IMT-system or other systems, the accuracy level is only a few metres.

Supporting various positioning methods to provide reliable and accurate UE location has always been a characteristic feature of the IMT-system and will be crucial to realize extreme new use cases in future terrestrial IMT systems towards 2030 and beyond. For the future terrestrial IMT systems towards 2030 and beyond, centimetre-level positioning accuracy within a few tens of millisecond latency should be achieved in the environment where Global Navigation Satellite System (GNSS) signals are unavailable, at least for some Industrial Internet of things (IIoT) cases and new services and applications. Furthermore, intelligently integrating data communication and UE positioning, including the resource (time, frequency, space) sharing, information (measurement information, CSI, RRM information and so on) sharing and intelligent decision making, could bring substantial benefits to both functionalities.

On top of cm-level positioning accuracy, positioning latency within a few tens of millisecond latency will often be desired. In addition to horizontal/vertical positioning accuracy and latency, other metrics such as power consumption, scalability/capacity, network deployment complexity, availability and security/privacy can be considered important design factors in future positioning technologies.

Naturally, it is difficult to meet various requirements with one technology and overcome all technical difficulties. For this reason, a combination of positioning technologies may be required, in addition to utilizing visible light, satellite signals, sensors, and communication signals as well. Ultra-dense

networks deployed to shorten the measurement distance and secure the line-of-sight path make it easier to attain the accuracy goal.

Line-of-sight/non-line-of-sight path detection and identification is key component to harness ultra-wide bandwidth and ultra-massive MIMO in a millimetric wave or terahertz band. Moreover, THz technology with wide contiguous signal bandwidth also allows for very fine spatial resolution which in its turn allows for identifying multipath components, thereby intrinsically improving the positioning accuracy.

Also, a sampling rate of more than 3 GHz on the receiver-side and sub-nanosecond synchronization between reference nodes are required for centimetre-level accuracy. Precision of synchronization is critical to positioning technologies that are based on time of flight (ToF) measurement of traveling waves, such as ultrasonic sound, light, and radio wave. Another positioning technology that requires synchronization is the stereo vision-based positioning. As the synchronization technology matures better toward 2030, it is conceivable that wireless space-time synchronization in future IMT to be available by around 2030, enabling Location Based Services to fully equipped with higher precision localization capability.

Furthermore, THz sensing permits combining traditional metrics such as range and Doppler with detailed imaging of the environment for even more accurate positioning. More specifically, high-frequency cm-level localization exploits Simultaneous Localization and Mapping (SLAM) to enhance the accuracy by collecting high-resolution RF imaging: 3D images using THz signals and then combined with angle- and time-of-flight information.

In fact, millimetre wave and THz frequency bands provide interesting new features, such as densification, highly directive pencil-like beam that not only improve communications, but also make possible centimetre-level positioning accuracy. Ultra-wide bandwidth and Extreme MIMO in a millimetre wave or THz band provide additional degrees of freedom and impart new performance gains for UE localization through the positioning technologies utilizing timing and angle measurements. Moreover, further enhancement of positioning accuracy including carrier phase positioning (CPP) based on cellular signals and AI/ ML positioning techniques can be considered. CPP has been used very successfully in GNSS for centimetre-level positioning or even millimetre-level positioning. However, the RAT-dependent CPP technique is so far not supported in IMT-system. The main motivation of using CPP in IMT systems towards 2030 and beyond is its capability to accurately determine the UE position with centimetre-level -accuracy without the need to use ultra-wide bandwidth or GNSS, which leads to more efficient usage of radio resources.

For NR positioning, it remains a challenge to support the required accuracy, reliability, scalability, and adaptability due to unpredictable radio propagation characteristics (e.g. LOS/NLOS link) in especially indoor scenarios. AI/ ML methods have recently been widely used to overcome these challenges with reasonable success. For the future terrestrial IMT systems towards 2030 and beyond, AI/ML positioning techniques can be considered for positioning enhancements. For example, in the absence of a line-of-sight path, fingerprinting or ray-tracing can be considered the most promising technologies with the help of AI/ML. So, the following issues need to be further investigated for positioning with AI/ML, at least including corresponding AI/ML training and algorithms, positioning efficiency and performance validation.

7 Technology enablers to enhance the radio network

7.1 RAN slicing

Network slicing is a network architecture that allows multiple independent logical networks to be created on mutually shared physical infrastructure. These logical networks, called slices, are configured to satisfy the specific needs of applications, services, customers, or network operators.

Each network slice could be administered by a mobile virtual network operator (MVNO) or by the customers themselves.

It is expected that future IMT-systems' RAN is a user-centric cell-free network using various frequency bands. Every RAN resource including radio unit association, frequency band, subchannels and processing time, should be flexibly partitioned (sliced) to guarantee packet flows with similar QoS requirements. Such RAN slicing supports 1) adaptive RAN slicing architecture for cell-free networks using massive MIMO and various frequency bands; 2) MIMO/beamforming/power control/transmission technology to overcome fading channels and mobility; and 3) spectrally efficient channelization and scheduling to ensure URLLC QoS by considering mobility and traffic characteristics. As billions of intelligent devices are expected to connect to future IMT-systems, RAN slicing techniques will be critically important for massive-broadband URLLC connectivity.

From a radio access perspective, RAN slices (RAN-S) could also be configured and created from the available radio resources. Recently, ML and AI techniques have been proposed for traffic forecasting and classification, dynamic resource availability prediction across the various radio interfaces, call/session admission control, and scheduling in RAN-S. The introduction of ML and AI in RAN slicing creates potential opportunities to evolve towards intelligent RAN-S.

7.2 Technologies to support resilient and soft networks for guaranteed QoS

As our economies and societies are increasingly reliant on IMT-systems, the availability and resilience of these radio network resources, and service assurances, have become crucial to maintaining highly efficient societies. Simultaneously, new services, such as immersive, holographic, tactile communications, and new media beyond 8K, will emerge in the future. Since QoS requirements vary from one user to another, the future network is proposed to be resilient and soft, i.e. user-centric, service oriented, flexible, and powerful in capabilities, guaranteed in QoS, and consistent in user experience. Several RAN technologies can be considered to satisfy these network requirements.

The QoS guarantee mechanism for user data transmission over an air-interface is obtained by considering the overall service characteristics and user air-interface channel environment. Examples include QoS identifier or similar attributes and CSI or potential attributes as defined in future networks. Combined with AI/big data technologies in L2/L3, networks can auto-adjust their QoS. Based on service feedback from UE, RAN can intelligently predict the trends of subsequent services and provide QoS guarantees in advance. Furthermore, deterministic RAN can be considered to meet the requirements of vertical industry scenarios and services. Zero-jitter in RAN can be achieved through efficient buffer mechanisms, enhanced scheduling strategies, and new ARQ and HARQ mechanisms.

Service-based and user centric RANs could be necessary to provide a soft capability to satisfy user-specific requirements. Typically, traditional networks are designed and planned to maximize capacity considering dynamic changes from the user demand and network load. Based on the concept of micro-services, the monolithic radio network can be split into multiple basic radio network functions or services and elements. With a flexible combination of these basic elements, future IMT-systems are expected to support on-demand generation of radio network functions. Alternative approaches propose a RAN with deep edge nodes that support AI, ultra-high throughput, and ultra-low latency.

7.3 New RAN architecture

The future network should integrate big data, control, information, and communication technology to meet diverse requirements. It presents strong interdisciplinary and cross-domain development. Moreover, with the continuous expansion of the network scale and its increasing complexity, the RAN architecture will be reformed and simplified to achieve its goal of strongest capability, simplest

architecture, and plug-and-play feature. Moreover, the network architecture should be designed to reduce the processing latency and enhance on-demand capabilities. In parallel, DOICT (data, operation, information, and communication technologies) convergence driven RAN architecture will be a trend that plays a more prominent role in future network design. Furthermore, native-AI enabled RAN functions can be used to enhance the network performance, reduce the cost, enable smart decision making in resource management, and realize digital transformation. It can also act as a service that supports new operations.

As the network scale continues to expand, network complexity has rapidly increased. Efficiency in data processing is reduced owing to redundancies among different layers, i.e. reordering, retransmission. Therefore, a thinner or lite protocol stack design could be necessary in future networks. RANs can consider flexible controlling mechanism designs to achieve the simplest architecture while maintaining the strongest capabilities, i.e. in the mapping of upper-layer and lower-layer protocol entities and selection of lower-layer data bearing channels.

Future networks should support the decoupling of signalling and data for robust control and on-demand data services. For instance, low-frequency bands can be used for signalling coverage to simplify mobility management and ensure users have real-time access. High-frequency bands can be enabled on-demand to support high-speed services. Additionally, a unified RAN architecture and signalling design could be considered to support diversity in radio interface technologies and new relationships among BSs and UEs, and wide-area and micro-area networks, which include RAN node cooperation and aggregation.

Alternative approaches for a novel RAN architecture are considered.

7.3.1 Support RAN nodes cooperation and aggregation

With the introduction of new services, applications, and scenarios, RAN nodes including BSs and UEs should function collaboratively to satisfy the QoS requirements of specific services, such as holographic connectivity, or enhance system performance in specific scenarios, such as multiple devices in proximity belonging to one user.

For holographic services, different profiles could be presented by different nodes, particularly in large scale activity. The end points could be BS(s) and/or UE(s), while different flows belonging to the same holographic service should be transmitted to their corresponding end points via separate interfaces, including wired and wireless interfaces. In this architecture, the functions and relationships of RAN nodes should be redefined and remodelled, such as introducing a new L2 protocol architecture for multiple nodes' cooperation. Furthermore, RAN procedures such as access control containing participating node(s), system information, paging, and mobility should be revisited while considering multiple RAN nodes. In the user plane, it is necessary to consider QoS satisfaction for coherent flows of specific service(s)/application(s) that could be transmitted through or received in multiple terminals.

In scenarios where a user owns multiple devices, UEs can cooperate in upper or PHY layers in the RAN. Here, service continuity should be guaranteed across different terminals, and a thinner protocol stack is applicable for a diversified controlling mechanism over air interface. Other technologies required to accommodate UE cooperation and aggregation include security for a group of UEs, connection control for the UE group, capability coordination and so forth. With UE cooperation and aggregation, adaptive network deployments can be realized by adding or deleting UEs in a UE group dynamically while maintaining service continuity. Consequently, UL transmission can be enhanced to improve the performance of the system.

7.3.2 User-centric architecture

In modern mobile networks, users are under the network's control. User-centric network (UCN) architecture is a native architecture that empowers users with the capabilities to define, configure,

and control the network functions related to their subscribed services. In contrast to the existing architecture, UCN will enable each user to have a dedicated virtual network that integrates all functions needed for their services. Such a user-centric radio network can dynamically match and update radio resources (i.e. frequency spectrum, TRxP, radio units) for the specific user in real-time, depending on the user's environment and services.

UCN users will be able to define the services they would like to receive and consider how to operate and manage them. For active services, users can configure policies for resource usage. UCN users will also be able to control the data that is generated or owned by them, as well as the corresponding process rights (i.e. authentication, authorization, and access control).

7.4 Technologies to support digital twin network

Traditionally, network optimization and innovation operate directly only on real networks. With real-time interactive mapping between the physical network and virtual twin network, digital twin networks (DTNs) can help efficiently and intelligently investigate, simulate, deploy, and manage novel technology networks. The top-level design for Digital Twin RAN (DT-RAN) should be considered to accommodate diverse physical RAN networks. As the infrastructure of a digital twin society, and also a typical example of DTN, DT-RAN can be developed as a brand-new autonomous network by digitalizing the physical network. It will have the ability to agilely perceive and adapt to the complex and dynamic environment and achieve network autonomy for its full life cycle in its planning, constructing, monitoring, optimizing, and healing phases.

Several novel technologies need to be considered to implement DT-RAN. The data collected from terminals, BSs, core networks, and network management in the IMT-system are aggregated to form a basic database after standardized data pre-processing operations such as cleaning, classification, association, and construction. Digital twin modelling technologies should support customizing and dynamically adjusting models to reduce the overhead of data collection and network transmission. These technologies should also support the on-demand selection and interconnection of different types of models, including data, simulation, and intelligence models. The high-fidelity and timeliness of DTNs should be ensured by using deviation correction technologies. For more robust network operations, DT-RAN should be able to use data from real wireless networks to train virtual scenarios and augment real data to construct more comprehensive virtual scenarios to facilitate more diverse training. As a critical functionality of DT-RAN, pre-verification should be driven by data and knowledge collaboratively, and a flexible simulation environment enabled by serviced based simulation architecture should be considered.

7.5 Technologies for interconnection with non-terrestrial networks

The interconnection of terrestrial IMT and non-terrestrial communications aims to expand future terrestrial IMT technology to support seamless interconnectivity with non-terrestrial networks (NTN), including satellite communications, High altitude platform stations as IMT BSs (HIBS) and UASs as IMT BS platform, commonly referred to as drones and a type of aircraft without a human pilot on board. Key technologies for this purpose consist of SDN/NFV, network slicing, network management, edge computing, free space optical communications and other network technologies in the context of future IMT.

HIBS is an IMT BS located on a platform that flies and remains in the stratosphere at an altitude of approximately 20 km and would be used as a part of terrestrial IMT networks. The stratosphere is a layer of the atmosphere far above the clouds, and it is unaffected by rain or snow and less affected by air currents. Consequently, these characteristics enable the flight of a stratospheric platform to be steadier when compared to flight in other layers of the atmosphere. Since HIBS operates at an altitude of approximately 20 km, it can provide services with the same latency as terrestrial mobile networks, among other features. The advantages of HIBS include: 1) a large service area radius of up to 100 km

using a single HIBS; 2) no modifications are required for normal terrestrial mobile phones; 3) robust and resilient networks that are unaffected by power outages or collapses because of natural disasters (earthquakes, tsunamis); and 4) provision of mobile communications in the sky (for flying cars, drones, etc.) and at sea (for ships, etc.), which are difficult to be covered by ground-based BSs.

UASs have a wide range in terms of size and weight and could be used in various business sectors in future smart cities. In the future, UASs can be used as BS platform or as a relay to form a temporary network to extend the mobile communication. The benefit of such UAS-assisted wireless communications is the flexibility and agility to provide on demand deployment of network coverage promptly, which is highly complementary to the fixed infrastructures in scenarios such as natural disaster and short-term events, such as concerts or big games in crowded stadiums. In some sense, UAS-assisted wireless communication can also bring the BS closer to the user, which could enhance the service quality and reduce power consumption for users. Moreover, UAS BSs can also serve as extended mobile sensors to enhance the sensing capability.

The interconnection of terrestrial IMT and non-terrestrial communications enhance the coverage of future IMT systems from the ground to air to space on a multi-layered basis. It would enable ubiquity of communications and is expected to enable new use cases, such as connections with unmanned systems, monitoring (video and data), mobile eMBB, IoT, logistics systems, and backhaul and smartphone interconnectivity. In addition to the coverage extension, when urban and sub-urban areas covered by ground-based IMT BSs are overloaded and/or when there is a high-capacity demand, they can offload their traffic to HIBS, UAS BS, and satellite network. Despite these benefits, as the technologies applicable to terrestrial communication networks might not be directly used in NTN, challenges are expected due to the highly dynamic network topology, different operational environment, and long propagation delay among others.

Mitigation solutions that will allow connectivity and seamless mobility between terrestrial and non-terrestrial networks should be studied.

7.6 Support for ultra-dense radio network deployments

Network densification is an effective way to fulfil the requirements of user experienced data rates, connection density, energy efficiency, spectrum efficiency, area traffic capacity, and coverage. Until recently, a BS can be decomposed into three functional modules, the central unit (CU), distributed unit (DU), and TRxP, connected mostly by fibre optics. In this architecture, an ultra-dense network (UDN) is typically implemented by increasing the densification of TRxPs. In UDN, there can be more TRxPs than the number of active users. In future RAN architectures, integrated access and backhaul (IAB), where the access link's framework is reused for the backhaul by multiplexing access and backhaul in time, frequency, and space domains, should be considered as a critical axis of UDN. It can facilitate replacing fibre optics with wireless could reduce both capital expenditures and operating expenses of backhaul links.

Furthermore, the IAB as well as mobile IAB can provide multi-hop capability, which is particularly useful to enhance coverage in mmWave or future THz deployment. In addition to the use of radio communications, other applications of THz, such as sensing, imaging, and localization may have a strong impact on the industry verticals. Therefore, considering these facts and poor propagation characteristics of mmWave and THz, the concept of ultra-dense integrated access and everything (UD-IAX) network should be examined to ensure the efficient use of high band spectrum. However, interference from these links inevitably increases as the information load becomes heavier. Accordingly, efficient control of interference in IAB is a challenging issue to solve.

7.7 Technologies to enhance RAN infrastructure sharing

The sharing of RAN infrastructure by multiple operators can help operators effectively reduce construction costs. In addition, it could also bring new possibilities to the business model of these operators. However, RAN infrastructure sharing surfaces new challenges in terms of transparency, reliability, rapid response and others. For instance, protecting user privacy while sharing effectively, exchanging QoS requirements and slice information across different operators, and ensuring the QoS of users from different operators are likely challenges to encounter. Technologies to enhance RAN infrastructure sharing should be considered in future IMT-systems, including trusted data storage and secure sharing. For example, blockchain technology can be used to achieve trustworthy enhancement of RAN storage. As a wireless access paradigm, blockchain can establish a decentralized and trusted system for physical links between service providers and clients. With the expansion of RAN infrastructure sharing, it is necessary to consider distributed AI technologies, such as FL, to satisfy the needs of multi-party cooperative computing between operators' RAN networks. Federated Learning (FL) can effectively solve the problem of data islands amongst different operators.

Despite various sharing and privacy requirements across different operators, these sharing techniques can be used to enhance RAN infrastructure. Moreover, service-based architecture of RAN can also be considered for RAN infrastructure sharing.

8 Conclusion

This Report describes technology trends of terrestrial IMT systems that are applicable to radio interfaces, mobile terminals, and radio access networks by considering the timeframe up to 2030 and beyond. These trends include emerging technologies and the technologies to enhance the radio interface as well as the radio network.

Further technical information and feasibility studies for higher frequency bands can be found in other ITU-R documents, and ITU-R is working on a report on the technical feasibility of IMT in bands above 100 GHz.

9 Acronyms, terminology, abbreviations

3D	Three dimensional
3GPP	Third-generation partnership project
ADC	Analogue-to-digital converter
AI	Artificial intelligence
AP	Access points
AR	Augmented reality
ARQ	Automatic repeat request
BS	Base station
CA	Carrier aggregation
CLI	Cross link interference
CMOS	Complementary metal oxide semiconductor
CP-CDMA	Cyclic prefix code division multiple access
CPP	Carrier phase positioning
CPU	Central processing unit
CSI	Channel state information

CT	Communication technology
CU	Central unit
DAC	Digital-to-analogue converter
DOICT	The Convergence of DT, OT, IT, and CT
D2D	Device-to-device
DT	Digital twin
DTN	Digital twin network
DT-RAN	Digital twin RAN
DTN	Delay and disruption tolerant network
DL	Downlink
eMBB	Enhanced mobile broadband
E-MIMO	Extreme-MIMO
FBMC	Filter bank multi-carrier
FDD	Frequency division duplex
FDM	Frequency-division multiplexing
FEC	Forward error correction
FL	Federated learning
GNSS	Global navigation satellite system
GPU	Graphics processing unit
HARQ	Hybrid automatic repeat request
HIBS	High altitude platform stations as IMT base stations
HR	Holographic radio
IAB	Integrated access and backhaul
IMT	International Mobile Telecommunications
ISAC	Integrated sensing and communication
IoT	Internet of Things
IIoT	Industrial internet of things
IT	Information technology
KPI	Key performance indicators
LDPC	Low density parity check
LOS	Line of site
MAC	Medium access control
MBB	Mobile broadband
MEC	Mobile edge computing
MIMO	Multi input multi output
ML	Machine learning
mmWave	millimetre wave
mMTC	Massive machine-type communications
MOSFET	Metal oxide semiconductor field effect transistor
MR	Mixed reality

MTC	Machine type communications
MUSA	Multi-user shared access
NOMA	Non-orthogonal multiple access
NTN	Non-terrestrial networks
OAM	Orbital angular momentum
OFDM	Orthogonal frequency division multiplexing
OMA	Orthogonal multiple access
OT	Operation technology
PA	Power amplifier
PAPR	Peak-to-average power ratio
PLS	Physical layer security
PDMA	Pattern division multiple access
PHY	Physical layer
PSTN	Public switched telecommunication network
QAM	Quadrature amplitude modulation
QoS	Quality of service
RAN	Radio access network
RAT	Radio access technology
RF	Radio frequency
RIS	Reconfigurable intelligent surface
RRM	Radio resource management
RTD	Resonant tunnelling diode
SBD	Schottky-barrier diode
SIC	Self-interference cancellation
SiGe	Silicon Germanium
SCMA	Sparse code multiple access
SLAM	Simultaneous localization and mapping
SL-IIoT	Sidelink enhanced industry internet of things
SSB	Single-sideband
SWaP	Size weight and power
TDD	Time division duplex
Tbit/s	terabits per second
THz	Tera-Hertz
ToF	Time of flight
UAS	Unmanned aircraft system
UCN	User-centric network
UDN	Ultra-dense network
UFMC	Universal filtered multicarrier
UL	Uplink
URLLC	Ultra-reliable low-latency communications

UTC-PD	Uni-travelling carrier photodiode
V2I	Vehicle-to-infrastructure
V2V	Vehicle-to-vehicle
VR	Virtual reality
XR	Extended reality

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