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The 6G Vision

1.1 Introduction

With the completion of third generation partnership project (3GPP) Release 15 of the 5G standard in June 2018, the research community has begun to shift their focus to 6G. In July 2018, ITU's Telecommunication standardization sector (ITU-T) Study Group 13 has established the *ITU-T Focus Group Technologies for Network 2030 (FG NET-2030).* FG NET-2030 will study the requirements of networks for the year 2030 and beyond and will investigate future network infrastructures, use cases, and capabilities. According to Yastrebova et al. (2018), current networks are not able to guarantee new application delivery constraints. The application time delivery constraints will differ in terms of required quality of service (QoS). For instance, for Internet of things (IoT) applications, the delay can be up to 25 ms, but connected cars will need 5–10 ms to get information about road conditions from the cloud to make the drive safe. Current cellular networks are not able to guarantee these new application delivery constraints. For illustration of these shortcomings, the authors of Yastrebova et al. (2018) mentioned that the end-to-end latency in today's 4G long-term evolution (LTE) networks increases with the distance, e.g. 39 ms are needed to reach the gateway to the Internet and additional 5 ms are needed to receive a reply from the server. Furthermore, the number of active devices per cell greatly affect the network latency. Measurements of highly loaded cells showed an increase of the average latency from 50 to 85 ms. Among others, the authors of Yastrebova et al. (2018) expect that future mobile networks will enable the following applications:

- Holographic calls
- Avatar robotics applications
- Nanonetworks

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- Flying networks
- Teleoperated driving (ToD)
- Electronic health (e-Health)
- Tactile Internet
- Internet of skills (IoS).

As a consequence, the network traffic will increase significantly with these new applications that will be enabled by technologies like virtual reality (VR) and augmented reality (AR). Even more exciting will be the widespread use and distribution of avatars for the reproduction and implementation of user actions. According to Yastrebova et al. (2018), avatar robotics applications can become one of the most important sources of traffic in future FG NET-2030 networks, involving new types of communications such as human-to-avatar (H2A), avatar-to-human (A2H), and avatar-to-avatar (A2A) communications. Importantly, taking into account the limited speed of propagation of light, the requirements for ultra-low latency should lead to the decentralization of future networks.

In academia, researchers from the University of Oulu's Centre for Wireless Communications launched an eight-year research program called *6G enabled smart society and ecosystem (6Genesis)* to conceptualize 6G. The first open 6Genesis seminar was held in August 2018. In Katz et al. (2018), an initial vision of what the sixth generation mobile communication system might be was presented by outlining the primary ideas of the 6Genesis Flagship Program (6GFP) created by the University of Oulu together with a Finish academic and industrial consortium. In this 6GFP program, 6G is investigated from a wide and realistic perspective, considering not only the communicational part of it but also looking into other highly relevant parts such as computer science, engineering, electronics, and material science. This integral approach is claimed to be instrumental in achieving truly novel solutions. Among others, the interrelated research areas of 6GFP aim at achieving distributed intelligent wireless computing by means of mobile edge, cloud, and fog computing. More specifically, intelligent distributed computing and data analytics is becoming an inseparable part of wireless networks, which call for self-organizing solutions to provide strong robustness in the event of device and link failures. Furthermore, VR/AR over wireless is considered one of the key application drivers for the future, whereby the information theory and practical performance requirements from the perspective of human psychology and physiology must be accounted for. As a consequence, perception-based coding should be considered to mitigate the shortcomings of existing compression–decompression algorithms in VR/AR. Future applications need distributed high-throughput local computing nodes and ubiquitous sensing to enable intelligent cyber-physical systems that are critical for future smart societies. Finally, techno-economic and business considerations need to address the question how network ownership and service provisioning models affect the design of radio access systems, including the potential analysis of high-risk technology enablers such as quantum theory and communications.

In September 2019, the world's first *6G white paper* was published as an outcome of the first 6G wireless summit, which was held in Levi, Finland, earlier in March 2019 with almost 300 participants from 29 countries, including major infrastructure manufacturers, operators, regulators as well as academia (Latva-aho and Leppänen, 2019). Each year, the white paper will be updated following the annual 6G wireless summit. While 5G was primarily developed to address the anticipated capacity growth demand from consumers and to enable the increasing importance of the IoT, 6G will require a substantially more holistic approach, embracing a much wider community. Many of the key performance indicators (KPIs) used for 5G are valid also for 6G. However, in the beyond 5G (B5G) and 6G, KPIs in most of the technology domains once again point to an increase by a factor of 10–100, though a 1000 times price reduction from the customer's view point may be also key to the success of 6G (Zhang et al., 2020). Note that price reduction is particularly important for providing connectivity to rural and underprivileged areas, where the cost of backhaul deployment is the major limitation. According to Yaacoub and Alouini (2020), providing rural connectivity represents a key 6G challenge and opportunity given that around half of the world population lives in rural or underprivileged areas. Among other important KPIs, 6G is expected to be the first wireless standard exceeding a peak throughput of 1 Tbit/s per user. Furthermore, 6G needs a network with embedded trust given that the digital and physical worlds will be deeply entangled by 2030. Toward this end, blockchain also known as distributed ledger technology (DLT) may play a major role in 6G networks due to its capability to establish and maintain trust in a distributed fashion without requiring any central authority.

Arguably more interestingly, the 6G white paper envisions that totally new services such as telepresence, as a surrogate for actual travel, will be made possible by combinations of graphical representations (e.g. avatars), wearable displays, mobile robots and drones, specialized processors, and next-generation wireless networks. Similarly, smartphones are likely to be replaced by pervasive extended reality (XR) experiences through lightweight glasses, whereby feedback will be provided to other senses via earphones and haptic interfaces.

1.2 Evolution of Mobile Networks and Internet

The general evolution of global mobile network standards was first to maximize coverage in the first and second generations and then to maximize capacity in the third and fourth generations. In addition to higher capacity, research on 5G mobile networks has focused on lower end-to-end latency, higher spectral efficiency and energy efficiency, and more connection nodes (Rowell and Han, 2015). More specifically, the first generation (1G) mobile network was designed for voice services with a data rate of up to 2.4 kbit/s. It used analog signal to transmit information, and there was no universal wireless standard. Conversely, 2G was based on digital modulation technologies and offered data rates of up to 384 kbit/s, supporting not only voice services but also data services such as short message service (SMS). The dominant 2G standard was the global system for mobile (GSM) communication. The third generation (3G) mobile network provided a data rate of at least 2 Mbit/s and enabled advanced services, including web browsing, TV streaming, and video services. For achieving global roaming, 3GPP was established to define technical specifications and mobile standards. 4G mobile networks were introduced in the late 2000s. 4G is an all Internet Protocol (IP) based network, which is capable of providing high-speed data rates of up to 1 Gbit/s in the downlink and 500 Mbit/s in the uplink in support of advanced applications like digital video broadcasting (DVB), high-definition TV content, and video chat. LTE-Advanced (LTE-A) has been the dominant 4G standard, which integrates techniques such as coordinated multipoint (CoMP) transmission and reception, multiple-input multiple-output (MIMO), and orthogonal frequency division multiplexing (OFDM). The main goal of 5G has been to use not only the microwave band but also the millimeter-wave (mmWave) band for the first time in order to significantly increase data rates up to 10 Gbit/s. Another feature of 5G is a more efficient use of the spectrum, as measured by increasing the number of bits per hertz. ITU's International Mobile Telecommunications 2020 (IMT 2020) standard proposed the following three major 5G usage scenarios: (i) enhanced mobile broadband (eMBB), (ii) ultra-reliable and low latency communications (URLLC), and (iii) massive machine type communications (mMTC). As 5G is entering the commercial deployment phase, research has started to focus on 6G mobile networks, which are anticipated to be deployed by 2030 (Huang et al., 2019).

Typically, next-generation systems do not emerge from the vacuum, but follow the industrial and technological trends from previous generations. Potential research directions of 6G consistent with these trends were provided by Bi (2019), including among others:

- *6G will continue to move to higher frequencies with wider system bandwidth*: Given that the spectrum at lower frequencies has almost been depleted, the current trend is to obtain wider bandwidth at higher frequencies in order to increase the data rate more than 10 times for each generation.
- *Massive MIMO will remain a key technology for 6G*: Massive MIMO has been the defining technology for 5G that has enabled the antenna number to increase from 2 to 64. Given that the performance gains have saturated in the areas of

channel coder and modulator, the hope of increasing spectral efficiency for 6G will remain in the multiple antenna area.

- *6G will take the cloud service to the next level*: With the ever higher data rates, short delays, and low transmission costs, many of the computational and storage functions have been moved from the smartphone to the cloud. As a result, most of the computational power of the smartphone can focus on presentation rendering, making VR, AR, or XR more impressive and affordable. Many artificial intelligence (AI) services that are intrinsically cloud based may prevail more easily and broadly. In addition to smartphones, less expensive functional terminals may once again flourish, providing growth opportunities in more application areas.
- *Grant-free transmissions could be more prominent in 6G*: In past cellular network generations, transmissions were primarily based on grant-oriented design with strong centralized system control. More advanced grant-free protocols and approaches will be needed for 6G. It is possible that the non-orthogonal multiple access (NOMA) technology may have another opportunity to prevail due to its short delay performance even though it failed to take off during the 5G time period.
- *mMTC is more likely to take shape in the older generation before it can succeed in the next generation*: mMTC has been one of the major directions for the next-generation system design since the market growth of communications between people has saturated. High expectations have been put on 5G mMTC to deliver significant growth for the cellular industry. Until now, however, this expectation has been mismatched with the reality on the ground. Therefore, the current trend appears to indicate that mMTC would be more likely to prevail by utilizing older technology that operates in the lower band at lower cost.
- *6G will transform a transmission network into a computing network*: One of the possible trademarks of 6G could be the harmonious operations of transmission, computing, AI, machine learning, and big data analytics such that 6G is expected to detect the users' transmission intent autonomously and automatically provide personalized services based on a user's intent and desire.

In his latest book "The Inevitable," Kevin Kelly described the 12 technological forces that will shape our future (Kelly, 2016). According to Kelly, nothing has happened yet in terms of the Internet. The Internet linked humans together into one very large thing. From this embryonic net will be born a collaborative interface, a sensing, cognitive apparatus with power that exceeds any previous invention. The hard version of it is a future brought about by the triumph of a superintelligence. According to Kelly, however, a soft singularity is more likely where AI and robots converge – humans plus machines – and together we move to a complex interdependence. This phase has already begun. We are connecting all humans and all machines into a global matrix, which some call the global mind or world brain. It is a new regime wherein our creations will make us better humans. This new platform will include the collective intelligence of all humans combined with the collective behavior of all machines, plus the intelligence of nature, plus whatever behavior emerges from this whole. Kelly estimates that by the year 2025 every person will have access to this platform via some almost-free device.

The importance of convergence of emerging key technologies, e.g. AI, robots, and XR, lies also at the heart of the 6G era with standards and enabled devices anticipated to roll out around 2030. 6G research is just now starting, even though 5G networks have not been widely deployed yet. A few countries, most notably Finland as well as China and South Korea, have taken the lead by launching 6G programs to avoid getting left behind.

1.3 6G Network Architectures and Key Enabling Technologies

1.3.1 Four-Tier Networks: Space-Air-Ground-Underwater

6G network architectures are anticipated to extend the 5G three-tier space-air-ground networks by integrating underwater networks, thus giving rise to four-tier space-air-ground-underwater networks with near-instant and unlimited superconnectivity in the sky, at sea, and on land. According to Zhang et al. (2019b), these large-dimensional integrated nonterrestrial and terrestrial networks will consist of the following four network tiers:

- *Space-network tier*: This network tier will support orbit or space Internet services in such applications such as space travel and provide wireless coverage via satellites. For long-distance intersatellite transmission in free space, laser communications represents a promising solution. The use of mmWave frequencies to establish high-capacity (inter)satellite communications may be another feasible solution to complement terrestrial 6G networks with computing stations placed on satellite platforms (Giordani and Zorzi, 2020). The integration of terrestrial and non-terrestrial networks poses a number of challenges and new open problems such as (i) large propagation delays, (ii) Duppler effect due to fast moving satellites, and (iii) severe path loss of mmWave transmission.
- *Air-network tier*: This network tier works in the low-frequency, microwave, and mmWave bands to provide more flexible and reliable connectivity for urgent events or in remote areas by densely employing flying base stations, e.g. unmanned aerial vehicles (UAVs).
- *Terrestrial-network tier*: Similar to 5G, this network tier will still be the main solution for providing wireless coverage for most human activities. It will

support low-frequency, microwave, mmWave, and THz bands in ultradense heterogeneous networks, which require the deployment of ultra-high-capacity backhaul infrastructures. Optical fiber will still be important for 6G, though THz wireless backhaul will be an attractive alternative.

- *Underwater-network tier*: Finally, this network tier will provide coverage and Internet services for broad-sea and deep-sea activities for military or commercial applications. Given that water exhibits different propagation characteristics, acoustic and laser communications can be used to achieve high-speed data transmission for bidirectional underwater communications. According to Huang et al. (2019), however, there is a lot of controversy about whether undersea networks are able to become a part of future 6G networks. Unpredictable and complex underwater environments lead to intricate network deployments, severe signal attenuation, and physical damage to equipment, leaving plenty of issues to be resolved.

1.3.2 Key Enabling Technologies

1.3.2.1 Millimeter-Wave and Terahertz Communications

Higher frequencies from 100 GHz to 3 THz are promising bands for the next generation of wireless communication systems, offering the potential for revolutionary applications. Technically, the formal definition of the THz region is 300 GHz through 3 THz, though sometimes the terms sub-THz or sub-mmWave are used to define the 100–300 GHz spectrum. The short wavelengths at mmWave and THz will allow massive spatial multiplexing in hub and backhaul communications. The THz band from 100 GHz through 3 THz can enable secure communications due to the fact that small wavelengths allow for extremely high-gain antennas with extremely small physical dimensions. The ultra-high data rates facilitated by mmWave and THz wireless local area and cellular networks will enable super-fast download speeds for computer communication, autonomous vehicles, robotic control, the so-called information shower, high-definition holographic gaming, and high-speed wireless data distribution in data centers. In addition to the extremely high data rates, there are promising applications for future mmWave and THz systems that are likely to evolve in 6G networks and beyond. These applications can be categorized into the main areas of wireless cognition, sensing, imaging, wireless communications, and position location/THz navigation (Rappaport et al., 2019).

A comprehensive literature review on the technical challenges in THz communications for B5G wireless networks was presented by Chen et al. (2019). In this survey, several key technologies for the realization of THz wireless communication systems were discussed in technically greater detail. Heterodyne reception is the most widespread receiving system in the THz band, whereby its core circuits usually include the circuits for frequency conversion, signal generation, and amplification. In the THz band, however, solid state amplifiers are lacking because the technology of compound semiconductor transistors is immature. Further, due to the lack of THz amplifiers, mixers become the first stage of receivers and affect their system performance. In the THz band, subharmonic mixers are usually used because they can mitigate the difficulty of local oscillators. The combination of metamaterials and semiconductor technologies has led to significant breakthroughs in dynamic THz functional devices, including THz amplitude and phase modulation. For the sake of channel characterization and propagation measurements in future THz wireless communication systems, it is vital to establish efficient channel models that maximize THz bandwidth allocation and spectral efficiency. Channel estimation in THz communication systems is challenging due to hybrid beamforming structures and the large number of antennas. Large-scale phased array antennas are suitable for THz communication systems to compensate for the high path loss and molecular absorption loss.

1.3.2.2 Reconfigurable Intelligent Surfaces

A brand-new wireless communication technology referred to as reconfigurable intelligent surfaces (RISs) – also known as large intelligent surfaces, smart reflect-arrays, intelligent reflecting surfaces, passive intelligent mirrors, artificial radio space, or programmable metasurface – has emerged recently (Basar et al., 2019; Tang et al., 2020b). RISs are often referred to as software-defined surfaces (SDSs) in analogy with the concept of software-defined radio (SDR). Accordingly, an RIS may be viewed as an SDS whose surface of electromagnetic material is controlled with integrated electronics and its response of the radio waves is programmed in software.

According to Basar et al. (2019), the distinctive characteristic of RISs lies in making the environment controllable by the telecommunication operators and thus giving them the possibility of shaping and fully controlling the electromagnetic response of the environmental objects that are distributed throughout the network. As a result, network operators are able to control the scattering, reflection, and refraction characteristics of the radio wave and thereby effectively control the wavefront (e.g. phase, amplitude, frequency, and even polarization) of wireless signals without the need of complex decoding, encoding, and radio frequency processing operations. In contrast to conventional wireless networks, where the environment is out of control of the telecommunication operators, RISs render the wireless environment a smart reconfigurable space that plays an active role in transferring and processing information. Consequently, RISs have given rise to the emerging concept of smart radio environments. In smart radio environments, the wireless environment is turned into a software-reconfigurable entity, whose operation is optimized to enable uninterrupted connectivity and high QoS guarantees. This is in stark contrast to conventional wireless networks, where the radio environment has usually an uncontrollable negative effect on the communication efficiency and QoS due to signal attenuation, multipath propagation, fading, and reflections from objects. RISs have the following distinguishable features (Basar et al., 2019):

- They are nearly passive and, ideally, do not need any dedicated energy source.
- They form a contiguous surface and, ideally, any point can shape the wave impinging upon it.
- They are not affected by receiver noise since, ideally, they do not need analog-to-digital converter (ADCs)/digital-to-analog converter (DACs) and power amplifiers.
- They have full-band response since, ideally, they can work at any operating frequency.
- They can be easily deployed, e.g. on facades of building, ceilings of indoor spaces, or human clothing.

1.3.2.3 From Network Softwarization to Network Intelligentization

In contrast to previous generations, 6G will be transformative and will revolutionize the wireless evolution from “connected things” to “connected intelligence.” According to Letaief et al. (2019), 6G will take network softwarization to a new level, namely toward network intelligentization. Software-defined networking (SDN) and network function virtualization (NFV) have moved modern communications networks toward software-based virtual networks. They also enable network slicing, which can provide a powerful virtualization capability to allow multiple virtual networks to be created atop a shared physical infrastructure. However, as the network is becoming more complex and more heterogeneous, softwarization is not going to be sufficient for 6G. Existing technologies such as SDN, NFV, and network slicing will need to be further improved by enabling fast learning and adaptation via AI-based methods. As a result, network slicing will become much more versatile and intelligent in order to support diverse capabilities and more advanced IoT functionalities, including sensing, data collection, analytics, and storage.

6G is expected to undergo an unprecedented transformation that will make it substantially different from the previous generations of wireless cellular systems. In particular, 6G will go beyond mobile Internet and will be required to support ubiquitous AI services from the core to the end devices of the network. Toward this end, Letaief et al. (2019) argue that 6G will require the support of the following three new service types beyond the aforementioned 5G eMBB, URLLC, and mMTC services:

- *Computation oriented communications (CoC)*: New smart devices call for distributed computation to enable key functionalities such as federated learning. Instead of targeting conventional QoS provisioning, computation oriented communication (CoC) will flexibly choose an operating point in the rate-latency-reliability space depending on the availability of various communications resources to achieve a certain computational accuracy.
- *Contextually agile eMBB communications (CAeC)*: The provision of 6G eMBB services is expected to be more agile and adaptive to the network context, including the communication network context such as link congestion and network topology, the physical environment context such as surrounding location and mobility, and the social network context such as social neighborhood and sentiments.
- *Event defined URLLC (EDURLLC)*: In contrast to the 5G URLLC application scenario with redundant resources in place to offset many uncertainties, 6G event defined uRLLC (EDURLLC) will need to support URLLC in extreme or emergency events with spatially and temporally changing device densities, traffic patterns, and spectrum and infrastructure availability.

6G will provide an information and communication technology (ICT) infrastructure that enables end users to perceive themselves as surrounded by a huge artificial brain offering virtually zero-latency services, unlimited storage, and immense cognition capabilities. 6G will play a significant role in responding to fundamental human and social needs and in helping realize Nikola Tesla's prophecy that "when wireless is perfectly applied, the whole Earth will be converted into a huge brain", according to Strinati et al. (2019). Toward this end, however, network intelligentization still has a long way to go by advancing machine learning technologies for 6G by taking more KPIs different from the traditional metrics into account, including situational awareness, learning ability, storage cost, and computation capacity (Kato et al., 2020). This also applies to the future intelligentization of 6G vehicular networks, where employing machine learning in vehicular communications becomes a hot topic that is widely studied in both academia and industry (Tang et al., 2020a).

When it comes to defining the unique challenges and opportunities of 6G, it is important to note that there is a strong notion that the nature of mobile terminals will change, with cars and mobile robots playing a more important role. Furthermore, we might witness the union of network convergence, meaning that we may see stronger dependencies between networking infrastructures and applications (David et al., 2019).

1.4 Toward 6G: A New Era of Convergence

According to the authors of Saad et al. (2020), the current deployment of 5G cellular systems is exposing the inherent limitations of this system, compared to its original premise as an enabler for Internet of everything (IoE) applications. IoE services will require an end-to-end design of communication, control, and computation functionalities, which to date has been largely overlooked. These 5G drawbacks are currently spurring worldwide activities focused on defining the next-generation 6G wireless system that can truly integrate far-reaching applications ranging from autonomous systems to XR and haptics. Importantly, the authors opine that 6G will not be a mere exploration of more spectrum at high-frequency bands, but it will rather be a *convergence of upcoming technological trends*. Toward this end, the authors presented a holistic, comprehensive research agenda that leverages those technologies and serves as a basis for stimulating more out-of-the-box research around 6G. While traditional applications will remain central to 6G, the key determinants of the system performance will be the following four new applications domains: (i) multisensory XR applications, (ii) connected robotics and autonomous systems, (iii) wireless brain-computer interaction, a subclass of human–machine interaction (HMI), and (iv) blockchain and distributed ledger technologies.

In addition to many of the 6G driving trends and enabling technologies discussed in previous sections, Saad et al. (2020) emphasized the importance of haptic and empathic communications and the emergence of new human-centric service classes as well as the *end of the smartphone era*. They argue that smartphones were central to 4G and 5G. However, in recent years there has been an increase in wearable devices whose functionalities are gradually replacing those of smartphones. This trend is further fueled by applications such as XR and HMI, e.g. brain-computer interaction. The devices associated with those applications range from smart wearables to integrated headsets or even smart body implants that can take direct sensory inputs from human senses, bringing an end to smartphones and potentially driving a majority of 6G use cases. They also expect that a handful of technologies will mature along the same time of 6G, e.g. quantum computing and communications, and hence potentially play a role toward the end of the 6G standardization and research process.

An interesting example of out-of-the-box 6G research was presented just recently in Viswanathan and Mogensen (2020). The authors claim that new themes are likely to emerge. Specifically, the future of connectivity is in the creation of *digital twin worlds* that are a true representation of the physical and biological worlds at every spatial and time instant, unifying our experience across these physical, biological, and digital worlds. Digital twins of various objects created in edge clouds will form the essential foundation of the future digital world. Digital twin worlds of both physical and biological entities will be an essential platform for the new digital services of the future. Digitalization will also pave the way for the creation of new virtual worlds with digital representations of imaginary objects that can be blended with the digital twin world to various degrees to create a mixed-reality, super-physical world. Smart watches and heart rate monitors will be mapped accurately every instant and integrated into the digital and virtual worlds, enabling new *super-human capabilities*. AR user interfaces will enable efficient and intuitive human control of all these worlds, whether physical, virtual, or biological, thus creating a unified experience for humans and the human transformation resulting from it. Dynamic digital twins in the digital world with increasingly accurate, synchronous updates of the physical world will be an essential platform for augmenting human intelligence.

The authors of Viswanathan and Mogensen (2020) outlined a vision of the future life and digital society on the other side of the 2030s. While the smartphone and the tablet will still be around, we are likely to see new man–machine interfaces that will make it substantially more convenient for us to consume and control information. The authors expect that wearable devices, such as earbuds and devices embedded in our clothing, will become common. We will have multiple wearables that we carry with us and they will work seamlessly with each other, providing natural, intuitive interfaces. Touch-screen typing will likely become outdated. Gesturing and talking to whatever devices we use to get things done will become the norm. The devices we use will be fully context-aware and the network will become increasingly sophisticated at predicting our needs. This context awareness combined with new man–machine interfaces will make our interaction with the physical and digital world much more intuitive and efficient. The computing needed for these devices will likely not all reside in the devices themselves because of form factor and battery power considerations. Rather, they may have to rely on locally available computing resources to complete tasks beyond the edge cloud. As consumers, we can expect that the *self-driving concept cars* of today will be available to the masses by the 2030s. They will be self-driving most of the time and thus will substantially increase the time available for us to consume data from the Internet in the form of more entertainment, rich communications, or education. Further, numerous *domestic service robots* will complement the vacuum cleaners and lawn mowers we know today. These may take the form of a swarm of smaller robots that work together to accomplish tasks.

Combining the multi-modal sensing capabilities with the cognitive technologies enabled by the 6G platform will allow for analyzing behavioral patterns and people's preferences and even emotions, hence creating a sixth sense that anticipated user needs. The resultant *network with the sixth sense* will allow for interactions with the physical world in a much more intuitive way.

1.5 Scope and Outline of Book

1.5.1 Scope

Building on the 6G vision outlined above, this book will describe the latest developments and recent progress on the key technologies enabling next-generation 6G mobile networks, paying particular attention to their seamless convergence. To help make and keep things concrete, the book will focus on the emerging Tactile Internet as one of the most interesting 5G/6G URLLC applications. Beside conventional audiovisual and data traffic, the Tactile Internet envisions the real-time transmission of haptic information (i.e. touch and actuation) for the remote control of physical and/or virtual objects through the Internet. The Tactile Internet opens up a plethora of exciting research directions toward adding a new dimension to the human-to-machine interaction via the Internet by exploiting context- as well as self-awareness. The underlying end-to-end design approach of the Tactile Internet is fully reflected in the key principles of the Tactile Internet. Among others, the key principles envision to support local area as well as wide area connectivity through wireless or hybrid wireless/wired networking. Furthermore, it leverages computing resources from cloud variants at the edge of the network. Some of the key use cases of the Tactile Internet include teleoperation, haptic communications, immersive VR, and automotive control. We will leverage our expertise and extend our recent work on immersive Tactile Internet experiences in unified fiber-wireless mobile networks based on AI enhanced multi-access edge computing (MEC), including cooperative computation offloading.

In addition, we will include our work on decentralizing the Tactile Internet in general and edge computing in particular via Ethereum blockchain technologies, most notably the so-called decentralized autonomous organization (DAO). Unlike AI-based agents that are completely autonomous, a DAO still requires heavy involvement from humans specifically interacting according to a protocol defined by the DAO in order to operate. We will elaborate on how this particular feature of DAOs (i.e. automation at the center and humans at the edges) can be exploited in the emerging concept of human-agent-robot teamwork.

Finally, we report on the state-of-the-art and our ongoing work on XR in the post-smartphone era. Specifically, we will elaborate on the implications of the transition from the current gadgets-based Internet to a future Internet that is evolving from bearables (e.g. smartphone), moves toward wearables (e.g. Google and Levi's smart jacket or Amazon's recently launched voice-controlled Echo Loop ring, glasses, and earbuds), and then finally progresses to nearables (e.g. intelligent mobile robots). Nearables denote nearby surroundings or environments with embedded computing/storage technologies and service provisioning mechanisms that are intelligent enough to learn and react according to user context and history in order to provide user-intended services. While 5G was supposed to be about the IoE, to be transformative 6G might be just about the opposite of Everything, i.e. Nothing or, more technically, No Things. Toward this end, we will elaborate on the *Internet of No Things* as an extension of immersive VR from virtual to real environments, where human-intended Internet services – either digital or physical – appear when needed and disappear when not needed. Building on Nissan's so-called invisible-to-visible (I2V) technology concept for self-driving cars, we will explore how the full potential of multisensory XR experiences may be unleashed in so-called Multiverse cross-reality environments and present our *extrasensory perception network (ESPN)* for the nonlocal extension of human "sixth-sense" experiences in space and time.

1.5.2 Outline

The remainder of the book comprises the following six chapters:

In Chapter 2, we elaborate on the Tactile Internet and its inherent human-in-the-loop (HITL) nature of human-to-machine interaction, paying close attention to the dichotomy between automation and augmentation (i.e. extension of capabilities) of the human. The Tactile Internet allows for a human-centric design approach toward creating novel immersive experiences and extending the capabilities of the human through the Internet by means of haptic communications and teleoperation. In this chapter, we pay attention to bilateral teleoperation as an example of HITL-centric applications and present an in-depth study of haptic traffic characterization and modeling. Specifically, we develop models of packet interarrival times and three-dimensional sample autocorrelation based on haptic traces obtained from real-world teleoperation experiments. Furthermore, we explore how wireless edge intelligence can be leveraged to help realize immersive teleoperation experiences in mobile networks that are unified with fiber backhaul and wireless mesh front-end networks based on low-cost data-centric optical fiber Ethernet, i.e. Ethernet passive optical network (EPON), and wireless Ethernet, i.e. wireless local area network (WLAN), technologies.

In Chapter 3, with the rise of increasingly smarter machines, we explore coworking with mobile robots – owned by mobile users (i.e. ownership spreading) or the mobile network operator – in greater detail by shedding light on the coordination of the human–robot symbiosis. A promising approach toward achieving advanced human–machine coordination by means of a superior process for fluidly orchestrating human and machine coactivity, which may vary over time or be unpredictable in different situations, can be found in the still young field of human-agent-robot-teamwork (HART) research. Toward this end, we investigate how context-awareness may be used to develop a HART-centric multi-robot task coordination algorithm that minimizes the completion time of physical and digital tasks as well as operational expenditures (OPEX) by spreading ownership of robots across mobile users. In addition, we explore how self-awareness can be exploited to improve the performance of multiple robots by identifying their respective capabilities as well as the objective requirements by means of optimal motion planning to minimize their energy consumption and traverse time to given physical and/or digital tasks. The proposed context- and self-aware HART-centric allocation scheme for both physical and digital tasks may be used to coordinate the automation and augmentation of mutually beneficial human–machine coactivities across the Tactile Internet based on unified communication network infrastructures.

In Chapter 4, we delve into the so-called missing middle that refers to the new ways that have to bridge the gap between human-only and machine-only activities for creating cutting-edge jobs and innovative businesses. This gives way to the so-called third wave of business transformation, which will be centered around human + machine activities. Toward this end, we formulate and solve the problem of joint prioritized scheduling and assignment of delay-constrained teleoperation tasks to available skilled human operators across unified communication network infrastructures with multiple objectives to minimize the average weighted task completion time, maximum tardiness, and average OPEX per task. We develop an analytical framework to estimate the end-to-end delay of both local and nonlocal teleoperation across the enhanced mobile networks under consideration and investigate the coexistence of conventional human-to-human (H2H) and haptic human-to-machine (H2M) traffic.

In Chapter 5, we explore the beneficial impact of cooperative computation offloading on the quality of experience (QoE) of mobile users with regard to average response time between mobile users, MEC servers, and remote cloud. Specifically, we investigate techniques that enable mobile users in self-organizing cellular networks to adaptively adjust their computational speed in order to reduce energy consumption or shorten task execution time under different scenarios. In our design approach, we take into account limitations stemming from both communications and computation by accurately modeling the fronthaul/backhaul as well as edge/cloud servers, while paying particular attention to the offloading decision making between mobile users and edge servers as well as edge servers and remote cloud. To allow mobile users to flexibly rely on their local computing resources by means of dynamic reconfiguration, the proposed self-organization framework lets mobile devices tune their offloading probability and computational capabilities adaptively, thus giving rise to a Pareto frontier characterization of the trade-off between average task execution time and energy consumption.

In Chapter 6, we explore the salient features that set Ethereum aside from other blockchains in more depth, including their symbiosis with other emerging key technologies such as AI and robots apart from blockchain-enabled edge computing. A question of particular interest hereby is how decentralized blockchain mechanisms – most notably Ethereum's concept of the DAO – may be leveraged to let emerge new hybrid forms of collaboration among individuals, which havenot been entertained in the traditional market-oriented economy dominated by firms rather than individuals. After elaborating on the commonalities of and specific differences between Ethereum and Bitcoin blockchains, we explain DAO in more detail and discuss the potential role of Ethereum and in particular the DAO in helping decentralize the Tactile Internet as a promising example of future techno-social systems via automation at the center and crowdsourcing of human assistance at the edges. Further, we explore the possibilities to extend the smart contract framework of the emerging blockchain Internet of things (BIoT) for enabling the nudging of human users in a broader Tactile Internet context by searching for synergies between the aforementioned HART and the complementary strengths of the DAO, AI, and robots.

Finally, in Chapter 7, we take an outlook on how future profound 6G technologies will weave themselves into the fabric of everyday life until they are indistinguishable from it. In our discussion, we show that future fully interconnected VR systems and the Tactile Internet seem to evolve toward common design goals. Most notably, the boundary between virtual (i.e. online) and physical (i.e. offline) worlds is to become increasingly imperceptible, while both digital and physical capabilities of humans are to be extended via edge computing variants with embedded AI capabilities. More specifically, we elaborate on the far-reaching vision of future 6G networks ushering in an anticipated 6G post-smartphone era, where smartphones will be increasingly replaced with wearables (e.g. smart jackets or voice-controlled glasses/earbuds/rings) and nearables (e.g. intelligent mobile robots). After explaining the reality–virtuality continuum in more detail, we introduce the so-called Multiverse to unleash the full potential of advanced XR technologies for the extension of human experiences, ranging from conventional VR to more sophisticated cross-reality environments known as third spaces. Further, we explore the potential of the recently emerging I2V technology concept, which we use together with other key enabling technologies (AI enhanced MEC, intelligent mobile robots, blockchain) to tie both online and offline worlds closer together in order to make the enduser “see the invisible” through the awareness of nonlocal events in space and time by mimicking the quantum realm via emerging multisensory XR and extrasensory “sixth-sense” human experiences.