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Review

Towards Enabling Haptic Communications over 6G: Issues and Challenges

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Abstract: This research paper provides a comprehensive overview of the challenges and potential solutions related to enabling haptic communication over the Tactile Internet in the context of 6G networks. The increasing demand for multimedia services and device proliferation has resulted in limited radio resources, posing challenges in their efficient allocation for Device-to-Device (D2D)-assisted haptic communications. Achieving ultra-low latency, security, and energy efficiency are crucial requirements for enabling haptic communication over TI. The paper explores various methodologies, technologies, and frameworks that can facilitate haptic communication, including backscatter communications (BsC), non-orthogonal multiple access (NOMA), and software-defined networks. Additionally, it discusses the potential of unmanned aerial vehicles (UAVs), network slicing, and wireless communication beyond 100 GHz and THz levels in improving haptic communication performance. The research emphasizes the importance of addressing security risks, optimizing resource allocation, and minimizing network congestion to unlock the potential of future networks and services. Aerial, ground, and underwater communication technologies are highlighted as key components of 6G networks, each with their advantages and challenges. The need for specialized equipment in remote areas to meet the bandwidth and latency requirements of haptic communication is underscored. The findings of this research contribute to a deeper understanding of haptic communication in the context of 6G networks and provide insights into potential solutions for overcoming the associated challenges.

Keywords: haptic communication; tactile internet; teleoperation; 5G and 6G cellular networks

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1. Introduction

The recent developments in communication networks enable many applications including high quality audio/video sharing [1]. Mobile communication has become an essential component of present-day life. It plays an important role in the economy, health, education, and many other industries [2–5]. Today, most of the population is connected through mobile communication networks globally [6,7]. After successfully connecting billions of smartphones and laptops through mobile internet, the focus of mobile internet has now been diverted towards the ubiquitous connectivity of multiple devices and machines, hence creating the Internet of Things (IoT) [8,9]. This transition has led mankind towards remote communication between a human being and some kind of physical device. Such data-intensive communications can result in mediums where the human beings can interact with each other remotely by touch (haptic communication) or actuation [10–12].

The upcoming 6G networks are set to provide ultra-reliable and low-latency communication which will make it possible for mission-critical applications, such as remote control of unmanned aerial vehicles (UAVs), information delivery, IoT communication, tactile internet, smart grids, and self-driving cars to be enabled [13]. The technology of Ultra-Reliable and Low-Latency Communications (URLLC) is becoming increasingly important for the upcoming sixth-generation (6G) networks. This service type is characterized by its stringent requirements of ultra-reliability and low-latency, which demand a decoding error probability of at least 10^{-5}. URLLC provides support for mission-critical applications, such as Unmanned Aerial Vehicles (UAVs) control information delivery, smart grids, tactile internet, and more. Previous communication systems were throughput-centric, based on the Shannon capacity formula, which assumes an infinite block length. In contrast, URLLC systems are reliable and latency-centric, and therefore use the finite block length capacity formula. Research regarding the channel coding rate and capacity bounds for finite block length can be found in [14]. Furthermore, URLLC will be essential for vertical and time-critical applications, such as factory automation and smart grids, which require perfect time synchronization between wireless mobile nodes and reference time sources [14]. The radio resource management of next-generation wireless communication networks, specifically for IoT, is of particular importance for URLLC. Many research topics in URLLC IoT networks revolve around radio resource management [15–17]. The emergence of 5G has driven the need for URLLC [18], which traditional networks cannot adequately support due to the requirement of achieving end-to-end latency of 20 milliseconds or more between users from end to end. This latency does not meet the requirements of the more advanced communication systems such as 5G and 6G [19,20].

The Tactile Internet is an advanced communication infrastructure that enables the low latency necessary for real-time interactive systems. This requires the implementation of suitable technologies and communication protocols in the different layers of an end-to-end architecture, such as the access network, core network, and customer premises equipment. Solutions introduced in these layers must meet the requirements of low latency, very short transmission delay, very high availability, ultra-reliability, security, and quality of service [21]. The past several years have seen a remarkable evolution in communication networks, with profound ramifications for our lives, politics, global affairs, and economy. This evolution in generations has resulted in a substantial shift in terms of coverage, security, cost, privacy, and many other aspects until the introduction of 5G, which divides its applications into three distinct categories: enhanced mobile broadband (eMBB), URLLC, and massive machine type communications (mMTC) [22,23].

Wireless communication networks have experienced rapid evolution over the years, enabling transformative advancements in connectivity and communication. With the advent of 5G networks, we witnessed significant improvements in data rates, latency, and capacity, paving the way for new applications and services. However, as technology continues to progress, the emergence of 6G networks is anticipated, bringing forth a new era of wireless connectivity. In this context, the quality of service (QoS) becomes paramount, as it directly impacts the user experience and enables a wide range of applications across industries. While 5G networks introduced classes of service such as URLLC, mMTC, and eMBB, 6G networks are expected to raise the bar even higher in terms of stringent requirements.

Current research in the field of information and computation technology (ICT) is increasingly focused on exploring the potential of next-generation networks such as SDN (Software-defined networking), 5G, and 6G. Among the research areas within the domain of 5G networks, particular attention is being given to optimizing D2D communication to enhance the quality of service. Researchers are investigating the structure of the frequency spectrum in relation to the working modes of D2D communication, aiming to meet predetermined system conditions and maximize network throughput [24].

One significant finding emerging from this research is the preference of D2D communication pairs to utilize full-duplex (FD) mode for short distances, as it fulfills system requirements. Consequently, a majority of communications within these distances take place using FD mode. These results underscore the advantages of employing FD communication in short-distance scenarios, as it provides better conditions and ensures a higher QoS compared to the QoS-D2D method.

Communication networks will provide various capabilities, e.g., ultra-reliable connectivity and low latency. However, 5G technology alone cannot fully meet all the demands in the near term, leading to the emergence of Beyond 5G (B5G) and Sixth Generation (6G) as the Next Generation Wireless Networks (NGWNs). Incorporating diverse paradigms and technologies such as Mobile Edge Computing (MEC), various radio access technologies, cellular Base Stations (BSs), Unmanned Aerial Vehicles (UAVs), Dedicated Short-Range Communications (DSRC), and D2D connections are essential for Next Generation Wireless Networks (NGWNs) [1]. NGWNs offer immense potential not only in the networking industry but also in verticals such as agriculture, entertainment, and healthcare. They enhance features such as global coverage, improved intelligence, enhanced spectral efficiency, cost and energy efficiency, and security. Key enablers and core technologies dominating NGWNs include Network Slicing (NS), Software Defined Networking (SDN), Network Function Virtualization (NFV), and MEC [25]. NS allows for the support of various network services, classified into eMBB, Communication-Everything (C2X), URLLC, and Massive Internet of Things (MIoT). NGWNs bridge the gap between societal and business demands. With 6G networks, the use cases expand to more stringent requirements in terms of QoS throughput, bandwidth, energy efficiency, and reliability [26]. SDN intelligently and centrally manages network traffic routing for software applications, while NFV packages network functions for deployment on commodity hardware. The high coupling between hardware and network functions can be avoided through NFV adoption. MEC alleviates backhaul network congestion, improves user experience, network performance, and resource optimization. It enables different industry sectors to achieve their desired QoS while reducing bandwidth usage [27]. Network Slicing (NS) in NGWNs instantiates a set of network functions on MEC cloud servers to provide low-latency communication services. However, challenges related to NS in NGWNs remain, including inter-slice and intra-slice orchestration, dynamic resource allocation, network slice control, resource sharing, slice/user admission based on QoS constraints, managing slice/user priority, traffic management, and congestion. Limited bandwidth and diverse slice requirements are the primary factors driving these issues, necessitating careful planning and efficient sharing techniques.

The following key enabling technologies will pave the way for new emerging applications, which are crucial for the realization of the 6G wireless network vision.

The healthcare sector is another area expected to benefit significantly from the deployment of 6G. Remote surgery, real-time tactile feedback, and optimized healthcare workflow are among the features that can elevate eHealth services to new levels. Ensuring the QoS requirements is particularly crucial in the healthcare sector, demanding mobility support, extremely low latency in the sub-millisecond range, and continuous connectivity with exceptional reliability of more than 90% [28]. Sixth-generation (6G) wireless networks are anticipated to provide the necessary stringent QoS requirements and enable a revolution in the healthcare sector.

Recent works have highlighted the profound impact of 6G technology on the future of wireless healthcare. For instance, Mucchi et al. [29] discuss how 6G technology can revolutionize the healthcare industry, emphasizing its potential to enhance telemedicine, wearable devices, and sensor networks. Their study underscores the role of 6G in enabling reliable and low-latency communication for healthcare applications. Similarly, in [30], authors have provided a comprehensive survey on the next generation of eHealth, where they explore the multidisciplinary aspects and potential use cases of 6G in healthcare. They discuss the integration of various technologies, such as artificial intelligence (AI), IoT, and edge computing, to achieve efficient and secure healthcare systems.

Furthermore, Chamitha de Alwis et al. [31] delve into the specific applications of 6G for healthcare, elucidating the transformative potential of 6G in facilitating improved patient care, remote diagnostics, and healthcare delivery in challenging environments. Their work emphasizes the need for seamless connectivity, ultra-reliable communication, and massive data handling capabilities offered by 6G networks to support advanced healthcare services.

While 5G networks have seen initial applications of extended reality (ER), which combines virtual, augmented, and mixed realities, it is still in its early stages compared to traditional 2D video streaming. To deliver the highly immersive experience promised by ER, devices require significantly higher throughput to handle higher-resolution videos with increased frame rates and color depth. This can result in a bandwidth requirement of 1.6 Gbps per device, surpassing the capabilities of 5G, particularly at the cell edges where widespread ER implementation is desired. Applications such as remote industrial control, remote surgery, and immersive gaming, which are potential use cases of interactive ER, also demand high reliability and low latency [32]. Once again, 6G wireless networks are envisioned to enable the realization of ER and its diverse applications.

In the coming decade, advancements in holographic display technology are expected to enable a truly immersive experience through remote rendering of high-quality holograms using mobile networks. However, achieving this vision requires tremendous bandwidth capacity, reaching the terabits per second (Tbps) range, to handle the volumetric data of 3D objects, as well as the resolution, frame rates, and color depths of 2D videos. Additionally, ultra-low latency is essential to create a truly immersive experience, along with precise synchronization of a multitude of interconnected streams necessary for hologram reconstruction [32]. The advanced capabilities of 6G networks are anticipated to make this future a reality.

Networks that enable seamless communication not only between humans but also between machines and humans in cyber-physical systems (CPSs) have triggered a revolution in the manufacturing industry, known as Industry 4.0. Industry 4.0 aims to minimize human intervention by establishing effective communication among large connected systems. To turn this vision into reality, remote industrial management is vital, requiring real-time control and management of industrial systems. Advanced robotics scenarios demand real-time data and extremely low latencies of around 100 microseconds to 1 millisecond for round-trip reaction times, while human operators can remotely monitor machines using tactile sensors, holographic communications, or virtual reality [33]. Once again, the demanding requirements of future 6G wireless networks are expected to support industrial automation.

The Internet of Everything (IoE) expands on the concept of the IoT by including things, people, data, and processes [34]. By integrating numerous sensing devices for various purposes, IoE enables identification, status monitoring, and intelligent decision-making tasks, opening up new and exciting possibilities. These sensors, capable of collecting data parameters such as temperature, light, position, velocity, and bio-signals, find applications in industrial domains, traffic control, smart cities, and healthcare systems [35]. Implementing such applications necessitates an extensive number of sensor devices and robust machine-to-machine communication. Therefore, 6G, with its enhanced capabilities, is expected to facilitate the realization of these applications.

For the aforementioned functionalities, the Tactile Internet (TI) is emerging after advancements in the cellular technologies, i.e., Fifth Generation (5G) and Sixth Generation (6G) with ultra-low latency, ultra-high-reliability and intelligent network connectivity, which enables the real-time control and haptic experience remotely [36–38]. The TI revolutionizes almost every sector of the society by shifting the focus from content delivery to skill set delivery network [39]. The 5G and 6G cellular systems could be an essential foundation on which the TI could establish connectivity and provide a breakthrough in the area of haptic communication [40,41]. The evolution of the TI is shown in Figure 1.

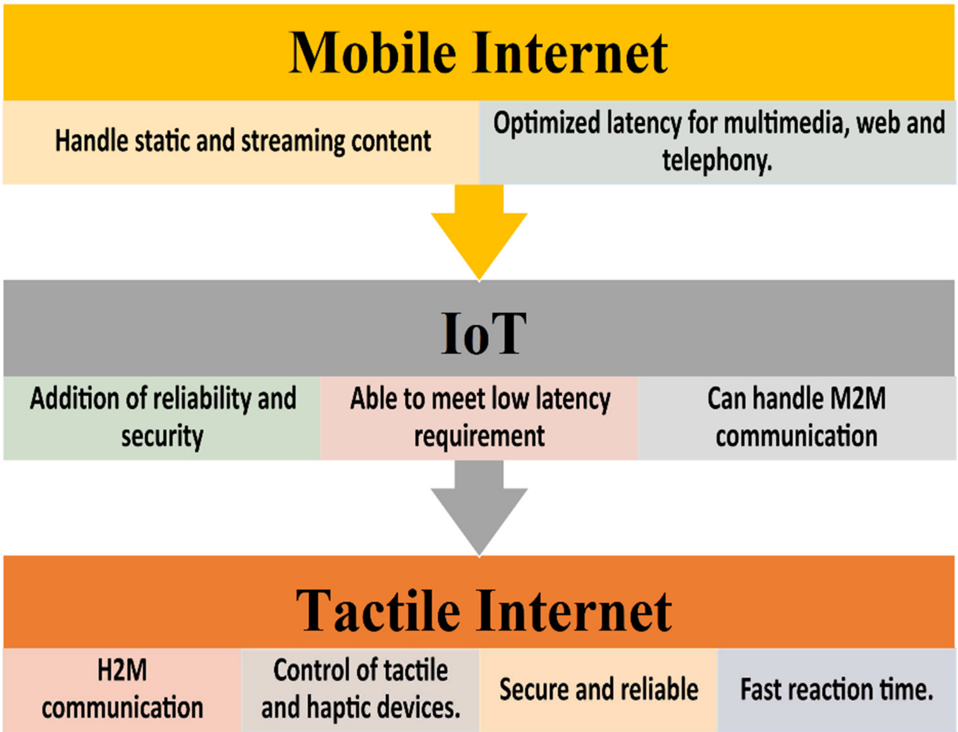

Figure 1. Evolution of the Tactile Internet.

The TI has several applications in the areas of healthcare, 3D printing, Virtual Reality (VR), smart grids, remote education, and remote immersion [42–44]. These applications are mostly delay-sensitive [45]. The delay required for haptic communication is the round trip delay of 1 ms [46]. Although this delay may depend on the applications as well, most of the applications of the TI require ultra-low latency rate which makes it challenging [47,48]. Therefore, along with the number of applications it brings issues and challenges as well for 5G and 6G network design [49]. The overview of different parameters of multiple cellular technologies (1G to 6G) is given in Table 1. This paper discusses the issues and challenges in enabling the tactile internet over 5G and 6G cellular networks. In terms of topic, our study is slightly related to [50]. However, the authors in [50] discussed only the trends to enable 6G network. In our work, we discuss the enabling technologies, issues, and challenges along with the applications of TI over 6G communication network in a comprehensive way. The organogram of this paper is given in Figure 2 and the contributions of this paper are as follows:

- The issues and challenges of TI that enable haptic communication in the mobile cellular generations are investigated.
- The proposed technologies and role of fog and edge computing as a unique architectural feature of the TI are discussed.
- Multiple performance evaluation parameters of TI are analyzed.
- Multiple applications of TI are discussed.
- Advantages and challenges of aerial, ground, and underwater communication technologies for 6G are discussed.
- Issues and challenges of TI over 6G are investigated.

Table 1. Overview of parameters of 1G to 6G technologies.

Generation	1G	2G	3G	4G	5G	6G
Technology	Analog cellular	Digital cellular	Broadband/IP, FDD, TDD	Broadband/IP, Wi-Fi, MIMO	www, IPv6	5G + Satellite
Data Speed	2.4 Kbps	9.6 Kbps	2 Mbps	50 Mbps	>1 Gbps	1 Tbps
Latency Rate	-	-	-	100 ms	10 ms	1 ms
Round Trip Time (RTT)	-	-	63.5 ms	53.1 ms	10–20 ms	1 ms
Core Network	PSTN	PSTN	Packet Network	Internet	Internet	Internet
Service	Only voice or message	Voice data & SMS	High-speed data, voice, video	Dynamic information access	Interactive multimedia, VoIP, AR, VR, IoT, Partially haptic communications	Interactive multimedia, VoIP, AR, VR IoT, haptic communications
Hand-off	Horizontal	Horizontal	Horizontal	Vertical	Horizontal & vertical	Horizontal & vertical
Bandwidth	-	-	-	-	mmWave and Terahertz bands	Terahertz and Optical bands
Network Slicing	-	-	-	-	Supported	Enhanced support
Energy Efficiency	-	-	-	-	Improved energy efficiency	Ultra-low power consumption
Spectral Efficiency	-	-	-	-	Improved spectral efficiency	Extreme spectral efficiency
Connectivity Density	-	-	-	-	Up to 1 million devices per square kilometer	Up to 10 million devices per square kilometer
Intelligent Connectivity	-	-	-	-	AI-enabled connectivity	Cognitive and self-learning capabilities
Security	-	2G encryption algorithms	Enhanced encryption	Enhanced encryption	Enhanced security mechanisms	Quantum-resistant encryption
User Experience	-	-	Basic internet browsing	Rich media experiences	Immersive AR/VR, Holography	Holographic and multisensory experiences
Applications	Voice calls, SMS	Basic data services	Mobile internet, video calls, multimedia streaming	Advanced mobile applications	Ultra-reliable low-latency applications	AI-powered applications, autonomous systems
Network Architecture	Cellular	Cellular	Cellular	Cellular	Cellular and satellite	Integrated cellular and satellite networks

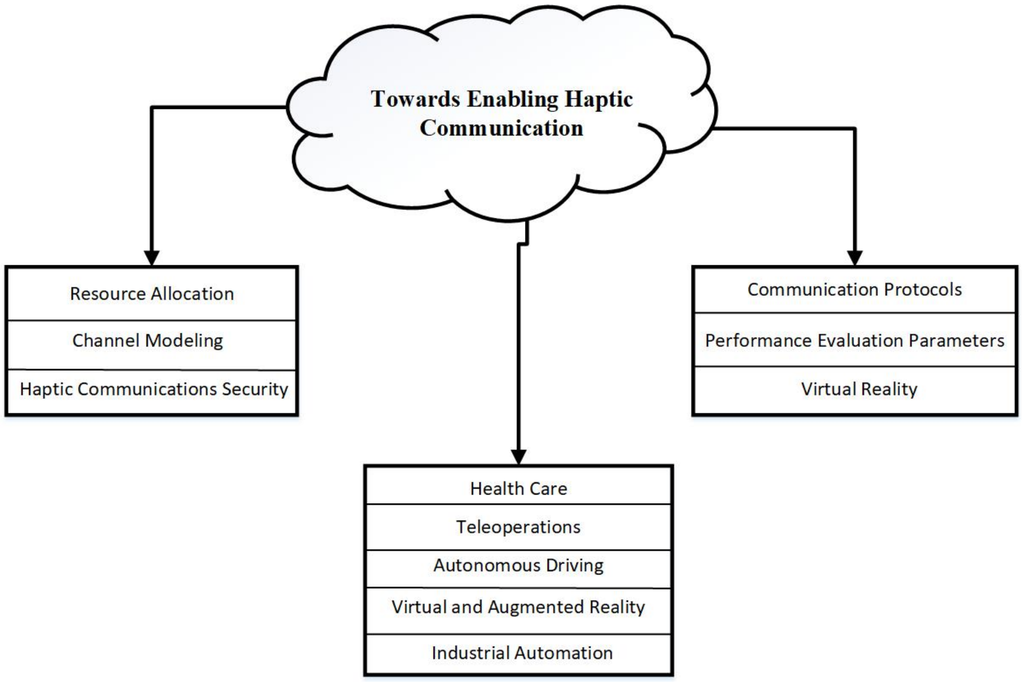

Figure 2. The overall organization of our review paper.

The rest of this paper is discussed as follows. Section 2 discusses the resource allocation in TI. Section 3 discusses the channel modelling for haptic communications. In Section 4, we discuss the haptic communication security and Section 5 discusses the communication protocols for haptic communications. Different performance parameters are discussed in Section 6. Section 7 covers virtual reality whereas advantages and challenges of communication technologies are discussed in Section 8. Applications of TI are discussed in Section 9. Section 10 discusses the enabling of haptic communication over 6G mobile networks and Section 11 discusses the issues and challenges of TI over 6G. Finally, Section 12 concludes this paper.

2. Resource Allocation in Tactile Internet

The increasing demand for multimedia services and the proliferation of devices have caused radio resources to become increasingly scarce [51]. As a result, it has become increasingly important and difficult to properly allocate radio resources for D2D-assisted haptic communications in order to guarantee the latency and reliability requirements of the control loop necessary for providing users an immersive experience [47]. The transmission of the haptic stream contains the control signal on the downlink and the feedback signal on the uplink [48].

The authors in [52] aim to minimize the usage of total bandwidth by jointly optimizing the downlink and uplink resource configuration. However, the uplink and downlink in this work do not form a control loop, which limits its application.

In [53], the authors pose D2D connectivity as a key technology for the efficiency of the cellular network through wireless systems of the fifth generation. In accordance with recent research progress, the authors implement D2D communication and its usage scenarios, present an explanation of D2D communication centered on spectrum division, duplexing and number of steps, level of control, and address interruption and architecture dimensions of D2D communication. They also highlight very recent research to acquaint the reader with the current developments in this regard. The technologies protected by these works comprise of file distribution, vehicular contact, web networks, video streaming, advertisement, and real-time applications. They also summarized the methods and models used and their standards. Finally, the authors explain the issues defined in various parts of D2D literature and state the very latest developments.

In [54], the authors discuss the use of backscatter communications (BsC) and non-orthogonal multiple access (NOMA) to improve the energy efficiency and capacity of wireless communications systems in the beyond 5G (B5G) era. The paper proposes the use of coded cooperative-NOMA in combination with BsC and presents simulation results showing the improved performance of the proposed method compared to traditional NOMA and BsC systems. The paper suggests that the combination of BsC and coded cooperative-NOMA can be a promising approach for improving energy efficiency and increasing capacity in B5G wireless communications systems.

The authors in [55] note that there is a need for potential communication services to co-exist with several current devices. Few of the implementations will require a smooth and quick association with different networks. A novel infrastructure is therefore required with new practices and features for various senses such as 3D-video, responsiveness (for example touch, sound, and feel). The packet distribution principle must always be imminent allowing for tremendous low latency and extreme precision latency. The extremely low latency criteria would allow the 2030 network to be decentralized. In addition, with the full application of TI services, the interaction between human avatars, etc., is possible. The reorganization of the network would result in a generalization of its function and a reform of network management concepts. Satellite networks can be commonly used for content distribution facilities, which at the same time is questionably effective for the introduction of new infrastructure needing extreme low delays due to the inherent constraints on the speed of light. Unmanned aerial vehicles (UAVs) and tethered UAVs can be extensively used as a flying application for low-density regions and difficult to access areas for delivering ultra-low delays in service.

In [56], the authors provide an extensive overview of the development of the telecommunications infrastructure through software-defined 5G/6G networks. They describe circumstances for the 5G/6G rollout, key technologies, and software defined networking (SDN). The SDN design offered open network access by modifying variations between machines on the network. Under the conventional IT network architecture, the routing process in the network which resolved the problem of complicated network design can be conveniently described. They then gave the future network design based on SDN, based on the principles of 5G/6G network design. Moreover, they discussed the new methods of allocating resources and managing them. Radio environment maps (REMs) may play a significant role in potential network analysis, because of the presence of innovative spectrum discovery and monitoring processes. While they have looked into the latest connectivity management technologies for 5G/6G networks and addressed how to fairly address the connected state mobility problem in extremely dense networks via SDN. The writers published a concise survey on SDN related conflict control of cellular 5G/6G networks. In addition, they provided a detailed overview of the interference graph (IG) abstraction which the SDN controller can use to configure network segments with several functional constraints. Furthermore, the writers outlined the study problems and accessible concerns on 5G/6G-based SDN networks and described potential paths for the next work.

In [57], multiple radio resource allocation for the haptic communication in the 5G enabled LTE-A networks is investigated. The radio resource allocation for the haptic communication system is a challenging task due to multiple constraints of the multiple access scheme in LTE-A networks. In this work, first, the requirements of the radio resource allocation for haptic communications are identified. After that, the problem is translated into the resource allocation problem which tackles the uplink and downlink constraints of the 5G LTE-A network. To reduce the complexity of the problem, the optimization problem is first decomposed and transform into binary integer programming. Extensive simulations have been conducted to show the effectiveness of the proposed scheme and results show that the resource allocation performed well for the 5G LTE-A network.

In [58], a novel radio resource allocation framework named Hap-SliceR for the 5G framework with haptic communication is proposed. This approach allocates the radio resources to the 5G network in a flexible way to utilize the maximum spectrum of radio resources. The Hap-SliceR strategy is based on the reinforcement learning for dynamic radio spectrum slicing. For this purpose, first, the radio resource slicing problem is modelled by using the Markov decision process and then solve it by mean of Q-learning. However, this Q-learning approach is computationally slow. Therefore, increasing the efficiency of radio resource slicing through post-decision requires learning that exploits the system dynamics. After that, the novel algorithm for network slicing is proposed that first identifies the requirements of the network and then formulate the unique allocation problem by considering the constraints of downlink and uplink multiple access schemes in LTE-A networks.

In [59], the key requirements and the solutions of haptic communication from a radio resource allocation perspective are proposed. The radio allocation problem is to deal with two different types of problems: symmetric and perceptual coding design. Due to the combinational nature of the problem, it becomes complex. To solve this issue, the problem is first decomposed and solved by using binary integer programming for resource block allocation. Furthermore, the resource allocation problem is solved by using greedy heuristic algorithms and by using the canonical duality theory and Hungarian method, near optimal solutions are proposed. The results acquired from simulations show that the proposed method outperforms the different classical algorithms.

3. Channel Modeling

The authors argue in [60] that network slicing is an effective way that meets the varied demands of 5G mobile networks, delivering the necessary stability and scalability related to potential network deployment. The study comprises of the basic principles underlying mapping committed and mutual slices, in addition to application-specific factors when the network slicing method is used across the Core Network (CN) and Radio Access Network (RAN). Special attention has been paid to linking RAN principles to network slicing. They also state that robust network slicing capacity has been discovered to meet the complex specifications of the upcoming 5G networks. When constructing network slicing based 5G networks, they emphasize on the problems that occur. Authors concentrate on the technical dimensions of the network's co-existence of devoted and mutual pieces. The authors discuss in detail the deployment possibilities of a modular wireless access system with an emphasis on network slicing and consequences on 5G mobile network architecture. Authors concentrate on the technological elements of the dedicated and reciprocal items co-existence of the network. The authors discuss in detail the implementation possibilities of an adaptable wireless access network with a focus on network slicing and effects on 5G mobile network design.

In [61], the authors present a specific and in-depth look at fundamental possibilities, problems and solutions to the development of potential spectrum wireless, sensing and positioning technologies over 100 GHz that will probably be a part of the 6G age. The paper identified recent legislative and standard group actions intended for promoting potential wireless schemes utilizing multi-GHz frequency channels over 100 GHz that can accommodate data rates of 100 Gbps. Authors state that a large number of exciting technologies should support future THz levels because computing power increases at the same pace to exceed the human brain's processing power. Many THz wireless applications will allow new perception, sensing, imaging, networks, and positioning abilities to be used by new human interfaces, autonomous vehicles, and automated devices, all empowered by THz's very high bandwidth and very short wavelength, which seems to be an assuring spectrum for coming wireless communications past the millimetre wave (mmWave) system. They also demonstrated how directional steerable antennas would allow mobile communication into the THz range, where the joint antenna gains will exceed the weather losses that were previously thought to be expensive. Antenna array systems would take advantage of new methods and physical designs such as three-dimensional noise modeling, beam shaping, hybrid beam shaping, and silence shafts, as these have demonstrated to provide substantial performance advantages, and also would resolve design restrictions such as the size of RF modules with a considerable number of antenna components. The authors review past work and introduced new measures of propagation over 100 GHz, analysis of cross-polarization discrimination, and measurements of partition failure for common building material.

In [62], the authors offered a comprehensive review of emerging technologies, including Machine Learning (ML), Quantum Computing (QC), and Quantum ML (QML). They also introduce their goal for the QC-and QML-assisted platform to allow wireless networks beyond 5G. First, the target facilities provided by evolving 5G communication networks and the complexities of accessible examination for the 5G communication networks were discussed. Afterwards, the latest trends in communications given by quantum, QC-aided, ML-aided, QC reinforced by ML, and QML were thoroughly reviewed. A system for 6G communication networks focused on ML, QML, and QC-aided has been suggested. Comprehensive discussions on numerous promising innovations, accessible science problems, and potential avenues for the study were given in the sense of the proposed system. Most specifically, the current 6G architecture has defined and addressed various potential supporting technology for network-organization, air device, network-edge, and user-side. The authors also describe network organization and-edge levels: the position of the suggested system for smart preemptive caching, smart MEC, resource allocation, multi-objective routing optimization, comprehensive IoT management, interoperability coordination, big data analytics, safe link security, and data privacy safety features have been addressed and suggested exhaustively.

In [63], the authors outlined wireless communication work and rulemaking beyond 100 GHz, examined current D band (110–170 GHz) transmission measurements, given NYU WIRELESS 140 GHz channel sounder architecture, and proposed tentative 140 GHz penetration failure measurements for different building resources. Penetration failure and total penetration loss of 140 GHz common resources that are not well studied are calculated and contrasted to 28 and 73 GHz common materials. The authors also describe a 140 GHz indoor measurement program that will be used to shape predictive indoor channel templates for different RX and TX antenna arrangements and multi-frequency divisions in combination with the previous 73 and 28 GHz indoor measurements performed at NYU WIRELESS. For mmWave indoor wireless network architecture, position tests, and a likely gigabyte Wi-Fi with the Internet of Things, the processing data and subsequent models can aid [64].

The current system of human-machine contact is outlined in [65], which focuses on the various approaches of emotion detection. Simultaneously, from the point of view of communication, the gap between the current human-machine interaction scheme and the proposed emotion communication scheme is compared. The authors then define the communication system of emotions and summarize the main technologies desired in the system. The authors described the design of the emotion communication system focused on the four principles: selection, coordination, interpretation and evaluation of the emotion that is desired in an emotion communication system. To meet the communication's consistency criteria for both sides when the emotion is conveyed as a kind of multimedia knowledge, the authors suggest an emotion transmission procedure that delivers high-level consistent support for emotion communication. Finally, the authors examine the actual performance of a pillow robot-based speech emotion communication scheme and demonstrate the viability and efficacy of transmitting an emotion.

The TI envisages full-time remote infrastructure control through Tactile sensors (haptics) and assisted by immersive audiovisual inputs in real-time. Applications such as telehealth or Industry 4.0 would need end-to-end intervals of up to 5 ms (minimum observable by the naked eye) and ultra-high-speed communications. VR video streaming needs to overcome many challenges to achieve the real time (maximum 5 ms end to end latency) and quality (5 Gbps) required by the TI.

The aim of [66] is to identify areas of accessible research and obstacles to allow VR for the Tactile Web. The authors established four fields of open science problems after a theoretical and practical assessment of state-of-the-art VR video streaming solutions. First, it is necessary to optimize and improve transport and application protocols. The authors believe that the research in this area is moving in the direction of adaptive streaming where tiles, prediction of viewport and infrastructure need to be thoroughly revised. Secondly, edge infrastructure will be necessary for moving computer-intensive tasks from lightweight VR customers and intelligently prefixing material to minimize latency. Second, it is important to synchronize the multi-sensor system (VR + haptics). Finally, to subjectively benchmark solutions, new evaluation infrastructures and new methods need to be created. Authors believe that this work opens up new research opportunities not only in the field of wireless network management and control but also in the challenging VR arena.

Sustained focus is important in the awareness, conditioning and locomotion of everyday human activities. An increase in persistent attention shows likely effects in several areas, including the management of mental ailments, such as attention deficit disorder, and the preparation of some employees, such as aircraft pilots, who function under high mental load conditions. The authors argue in [67] that through preparation, vigilant monitoring can be improved. Nonetheless, a technique to fully utilize the human haptic pathway in the course of preparation has not been explored by any comprehensive research. Thanks to the fundamental focus function and exclusive features of the haptic system, haptics-mediated attention coaching provides tremendous promise. Training in haptics-mediated care is a cross-disciplinary study involving cognitive neuroscience, haptics, and psychophysiology. Exploring the neural and psychological attention methods in tasks that use the haptic channel can also foster an understanding of the mechanism of neuroplasticity in humans. The authors propose an innovative use of haptic tools that improve the ability of the human brain to maintain continued attention through the haptic channel. Since haptic experiences, such as the ability to control power, are a natural human feeling, the existing computer games may theoretically be revamped by adding realistic force feedback simulations, raising the cautious workload of players.

4. Haptic Communications Security

In [68], the authors discuss the security requirements for the 6G networks and describe a solution that emphasizes the insertion of trust to address distributed denial of service (DDoS) attacks into the networks. The authors argue that security risks will increase in a world where digital devices and hackers remain within the borders of the digital world. In particular, hacking can be harmful when cars, houses, vessels, harbor transportation facilities, transportation hubs and storehouses, energy supply grids, energy production and storing systems are linked to a digital network. If hacking is possible, many real-world crimes may be possible such as theft of goods, razing other's property, and many other crimes.

The authors suggest in [69] that trust should be embedded in the network itself as an inherent function to automate backtracing of attacks, avoid successful distributed denial of service attacks and additional security functionality using cloud-based automation to support inexpensive and low-power devices. The authors further argue that security at the Internet level will not be enough when the physical and digital worlds intersect narrowly due to the heavy dependency on information security from physical security.

In [70], for 5G/6G wireless networks, the authors are proposing a new multiple access method for broad wireless communication, called Delta orthogonal multiple access (DOMA). The authors state how each cohort of cellular wireless methods has been differentiated by a different multiple access approach. First-generation (1G) networks focused primarily on multiple access frequency division (FDMA), while second, third and fourth-generation systems used Code Division Multiple Access (CDMA), Time Division Multiple Access (TDMA) and Orthogonal Frequency Division Multiple Access (OFDMA) techniques respectively.

For 5G cellular networks, although many deployments and standardization attempts are nevertheless underway, the authors foresee no innovative multiple access technologies that use significantly wider spectrum ranges (up to 60 GHz) and the introduction of Non orthogonal Multiple Access Scheme (NOMA) in addition to the existing Orthogonal Frequency Division Multiple Access (OFDMA). By adopting higher frequency spectrum bands such as mmWave bands in 5G, air interface would pose significant propagation problems due to extreme path-loss and need for beam orientation. This can be partly mitigated with the ultra-dense utilization of access points, which requires complex management and collaboration between dispersed APs to minimize the effects of co-channel interference resulting from overlapping adjacent cell coverage areas.

5. Communication Protocols

In [65], the authors suggest an emotion communication system based on NLOS mode to disrupt the constraint of the conventional human-machine contact framework. They describe the emotion first as one form of multimedia that is comparable to audio and video formats. It is not only possible to recognize the emotional knowledge, but also to transmit it over long distances. Instead, because of the real-time needs of the interactions between the participating parties, and emotional contact procedure is suggested that offers reliable support for emotional communication. An emotion communication system is developed for the pillow robot voice, where the pillow robot serves as a visualization tool for consumer emotion. Eventually, in the landscape of a long-distance contact among a pair of mother-child people, the real-time operation of the whole communication mechanism to determine the viability and efficacy of emotion communication is investigated.

The authors research and analyze the latest migration strategies provided by virtualization platforms such as docker and Kernel-based Virtual Machine (KVM) in [71] and suggest an application-level migration protocol that avoids the former's disadvantages. In a latency-sensitive application such as a gaming program, the server needs to be transferred throughout the gameplay sessions between various hosts. The authors introduce the implementation of the suggested protocol as a proof of concept to the users and research the transition in depth. They further research and analyze different migration approaches and suggest a framework for application-level migration, now referred to as Agile Cloud Migration (ACM). The framework is designed to rapidly and regularly deploy concurrent and latency-sensitive applications through multiple internet servers. The protocol requires certain application architecture designs such as engine isolation from its state to optimize the migration, and while keeping the entire migration process transparent to the user. Using theoretical approximations, the measurements of transfer time are deliberated in detail and proven using the measurements made on the concrete implementation of the ACM protocol.

Taking advantage of the recent advances in 5G and ultralow latency networking, AI in general, and robotics, the authors emphasize in [72] the advent of a radically new Web that will allow digital capabilities to be delivered. The authors present their perspective on an innovative internet generation, the Internet of Skills, where sophisticated ultra-low latency, AI, and advances in robotics can allow skills to be distributed throughout the world securely and cost effectively. They identify the technical challenges that need to be solved to enable such a dream, i.e., the creation of a 5G Tactile Network, unified haptic codecs, and AI to allow zero-latency networks to be viewed. They claim that the Web of Skills will revolutionize business processes and company functionality by allowing the distribution of physical experiences locally (and globally) and will transform the way teaching, training, and communication are conducted in the customer world. They claim that it would become a catalyst for skill set transfer making it an essential technology for service-driven markets. Finally, they discuss social challenges related to the Internet of Skills, emphasizing both business and societal opportunities enabled by the novel concept of the Internet of Skills.

6. Performance Evaluation Parameters

In [73], the detailed comparison of the multiple parameters of the 1G to 5G technologies is discussed. Furthermore, the prospects of the 6G future technologies are proposed to discuss further advancements in the relevant area. The detailed comparison and properties discussed in this work are summarized in Table 1, which gives the broad overview and features of the 1G to 6G technologies and Table 1 also shows which technology enables TI in future networks. The 5G and 6G systems will increase performance and maximize user quality of service (QoS) by several folds more than 5G along with some exciting features. It will protect the system and secure user data. It will provide comfortable access to haptic communications.

In [74], the author projected a framework for Distributed Event-Triggered Communication and Control (ETCC) of Linear Multi-Agent System (MAS) under the TI for the data reduction of every agent. Firstly, the proposed work reflects the ETCC data reduction scheme both for the communication and controller update to each agent under the TI. This framework highlights that with this arrangement, the ultra-low latency and data reduction are reinforced as the output feedback of ETCC. The proposed work proves that the agreement of MAS can be accomplished asymptotically. Finally, it is revealed that the proposed communication and control approach satisfies in the reduction of mutually the frequency of the communication and controller updates as well as excluding Zeno behavior.

In [75], the authors discuss the design challenges and their solutions to enabling the TI. This work first focuses on the requirements of haptic communications in the context of TI and then highlights the design challenges of TI over cellular networks. This work focuses on designing such an architecture that enables haptic communications without changing the existing architecture of the communication system with efficient network slicing and resource allocation, by achieving ultra-reliable connectivity along with the reduction in round-trip latency. The latency rate is increased by using optical transport as a backhaul medium and by increasing the computational power of the nodes. This work shows that haptic communications can be accomplished through a slight change in architecture and interface design at the wireless edge.

In [76], a novel approach to reduce the round-trip latency and network congestion is proposed. This problem is catered to by introducing small scale clouds which consist of a small number of cells. The edge computing facilities are present in the micro-cloud, and this micro-cloud is connected with the mini-clouds which have furthermore computation capabilities. By introducing multi-level clouding results in reducing the round-trip latency and network congestion. This high latency rate will encourage the TI by which the emotions can be transferred in real-time.

The TI structure defined networks in the core of the cellular network and mobile edge computing in multilevels to reduce round-trip latency as discussed in [77]. This approach uses the motivation behind the software define networks which have centralized core controller with a global knowledge of the network along with the concept of network function visualization. The results of this work show that the round-trip latency is decreased with the decrease in the bandwidth and by shifting the communication process from the core network controller to the mini-cloud unit.

A system model for a multi-level cloud-based TI system is discussed in [69]. In this work, the focus is to achieve the low round-trip latency which enables haptic communication over TI. For this purpose, the multi-level cloud-based system is proposed in which computations are performed on different cloud levels to avoid delay. This work is quite similar to the [76], but in this work along with optimizing the latency rate, energy efficiency is also achieved. Although in [69] the target is achieved by using the same approach of multi-level cloud computing, the optimization of the network layers and cloud units is ignored. It is better to optimize the number of first level clouds connected to mini-clouds to reduce the round-trip latency.

In [78], the authors proposed the key architecture changes in the existing 5G cellular network to enhance the cost, energy efficiency, stability, security, and latency. For this purpose, the authors' proposed the decomposition of a mobile cellular network function and allocate it to the cloud network. To implement this concept the software defines network and network visualization concepts are used in which cloud computing is involved to reduce the computational complexities which result in the reduction of end-to-end latency.

In [79], the authors highlight the key networking solutions to enabling the TI in the flexible 5G networks and beyond. This work focuses on the recent progress in the area of TI and its enabling technologies. The state-of-the-art techniques discussed in most of the literature is to integrate the software-define radios and network function virtualization along with edge-fog computing to overcome the issue of 1 ms latency rate, which enables TI.

An approach to achieve the goal of 1 ms latency over the 5G network is proposed in [80]. The authors proposed that the centralized controller in the network with global information of the entire system overcome the issue of 1 ms round-trip latency. This system architecture employs software defined network along with multi-level mobile edge computing to enable TI. The modular testbed to test the large variety of haptic communications applications is discussed in [81]. Haptic systems are tested based on characteristics and validation of many aspects of end-to-end delay. Therefore, a testbed using multi-block testbed architecture is proposed by the authors. In this architecture, depending on the use case to be tested, the blocks are reconfigured and add/remove module options are available. Moreover, the testbed tools are designed to extract the information of the latency of sub-blocks and modules in use to support the research and development.

In [82], authors propose a queueing function for a pair of Power Domain Non-orthogonal multiple access (PDNOMA) based TI users in C-RANs. Authors consider a more practical scenario between end-to-end TI users by incorporating RRH and BBU queueing delays. To minimize these delays, the problem is first treated as a non-convex optimization problem. Then it is solved by successive convex approximation (SCA) and the difference between two convex functions (DC). This solution allows controlling the delays encountered among TI users. By using the proposed queueing model these delays between TI users are significantly improved enabling less usage of transmission power for each transmission between users. In [83], a resources allocation (RA) algorithm using admission control (AC) is proposed for users which are using TI services in OFDMA based C-RAN network. To maximize user experience, delays encountered due to BBUs, RRHs and front hauls are minimized. This is possible when RA is considered a non-convex problem. To solve it, successive convex approximation (SCA) is applied which reduces transmission power consumption. The performance of this algorithm is evaluated by the service acceptance ratio (SAR).

7. Virtual Reality

Virtual Reality (VR) haptic technology offers an extra feature to the VR technology by letting users feel the virtual environment via the sense of touch, in addition to visual and aural perception. One method to achieve this haptic feature is to add a passive haptic device to the VR.

In [84], the framework of haptic retargeting is proposed, which supports passive haptics for multiple virtual objects by using a single physical prop. This task will be achieved by providing the haptic feedback in a VR environment by warping up the virtual space by matching the location of a prop in someone's surroundings. The warping has been achieved by using three methods: body, word and hybrid warping, which allows passive haptics in a VR that is different from the physical one. These three techniques of warping enable a better sense of presence in VR.

In [66], the challenges in the VR video streaming technologies for the TI are discussed. To achieve the real-timeliness and high quality, the network must have an ultra-low latency rate that can be possible by TI. However, it is still a challenging task in VR to achieve ultra-high-speed video streaming. For this purpose, the authors suggest that some areas of the TI must be addressed by the researchers properly, i.e., transport and application protocols, edge infrastructure, and VR and haptic devices must be synchronized.

The control strategies for the haptic interface in VR are proposed in [85]. The force and position control strategies have been used to improve the haptic interface in VR. Furthermore, the three-stage energy compensation controller was used to avoid the instability caused by the energy leakage. This technique efficiently controls the haptic rendering destabilization, but loses control sometimes in the position control mode and may increase the instability threshold. Therefore, the energy compensation controller along with fuzzy impedance controller gives better position control and improves stability in the haptic interface.

8. Advantages and Challenges of Communication Technologies

Sixth-generation (6G) networks are the next generation of wireless communication networks, and they are expected to offer significantly higher speeds, capacity, and performance than previous generations of networks. While 6G is still in the development stage and its exact features and capabilities have not yet been fully determined, it is expected to incorporate a variety of different communication technologies, including aerial, ground, and underwater communications.

Aerial communication refers to the transmission of information through the air, typically using wireless technologies such as radio waves or microwaves. In the context of 6G networks, aerial communication is likely to continue to play a significant role in providing coverage and capacity for a wide range of applications, including mobile communication, IoT, and machine-to-machine (M2M) communication [86,87].

Ground communication refers to the transmission of information through cables or wires that are physically connected on the ground. In the context of 6G networks, ground communication is likely to continue to play a role in providing high-bandwidth, high-capacity communication for applications that require low latency and high reliability, such as industrial control and automation [88,89].

Underwater communication refers to the transmission of information under water, typically using sound waves or light waves. In the context of 6G networks, underwater communication is likely to play a role in providing communication for a variety of underwater applications, such as offshore oil and gas exploration, military operations, and ocean monitoring [90,91].

8.1. Advantages of Aerial Communication in 6G

- Wide coverage: aerial communication technologies can cover large geographical areas, making them useful for long-distance communication and for providing coverage in remote or hard-to-reach areas [92].
- High speed: aerial communication technologies are expected to offer significantly higher speeds in 6G networks, making them suitable for applications that require fast communication [93].
- Flexibility: aerial communication technologies can be easily deployed and relocated, making them suitable for use in dynamic environments [94].
- High capacity: aerial communication technologies are expected to offer significantly higher capacity in 6G networks, which can support the transmission of large amounts of data [95].

8.2. Challenges of Aerial Communication in 6G

- Interference: aerial communication technologies are vulnerable to interference from other sources, such as other wireless devices or physical obstacles [96].
- Limited bandwidth: the available bandwidth for aerial communication is limited, which can affect the quality and capacity of the communication [97].
- Weather: aerial communication technologies can be affected by weather conditions, such as rain, fog, and thunderstorms, which can reduce the quality and reliability of the communication [98].
- Security: aerial communication technologies are generally less secure than ground-based technologies, as they are easier to intercept or disrupt [99].

- Energy efficiency: aerial communication technologies can be energy-intensive, which can be a challenge for applications that require long-term or continuous operation [100].

8.3. Advantages of Ground Communication in 6G

- Reliability: ground communication technologies are generally more reliable than aerial communication technologies, as they are less vulnerable to interference and weather conditions [101].
- Security: ground communication technologies are generally more secure than aerial communication technologies, as they are harder to intercept or disrupt [102].
- High bandwidth: ground communication technologies are expected to offer significantly higher bandwidth in 6G networks, which can support high-quality and high-capacity communication [103].
- Low latency: ground communication technologies can offer low latency, which is important for applications that require real-time communication [104].

8.4. Challenges of Ground Communication in 6G

- Limited coverage: ground communication technologies are limited to the physical location of the cables or wires, which can make it difficult to provide coverage in remote or hard-to-reach areas [105].
- Inflexibility: ground communication technologies are generally less flexible than aerial communication technologies, as they require the physical installation and maintenance of cables or wires [105].
- Cost: the installation and maintenance of ground communication technologies can be costly, especially in large or complex networks [105].
- Vulnerability to physical damage: ground communication technologies are vulnerable to physical damage, such as cuts or breaks in the cables or wires, which can disrupt the communication [105].
- Limited mobility: ground communication technologies are generally less mobile than aerial communication technologies, as they are tethered to the ground [105].

8.5. Advantages of Underwater Communication in 6G

- Security: underwater communication technologies are generally more secure than aerial or ground communication technologies, as they are harder to intercept or disrupt [106].
- Low interference: underwater communication technologies are less vulnerable to interference from other sources, as there are fewer sources of interference [106].
- Long range: underwater communication technologies can support long-range communication, as sound waves can travel long distances through water [106].
- High data rates: underwater communication technologies are expected to offer significantly higher data rates in 6G networks, which can support the transmission of large amounts of data in real-time [106].

8.6. Challenges of Underwater Communication in 6G

- Limited coverage: underwater communication technologies are limited to the physical location of the water, which can make it difficult to provide coverage in areas that are not near bodies of water [107].
- Complexity: underwater communication technologies can be complex to design and implement, as they need to account for the unique properties of water and the underwater environment [107].
- Cost: underwater communication technologies can be costly to develop and maintain, due to the specialized equipment and expertise required [107].
- Environmental factors: underwater communication technologies can be affected by environmental factors such as temperature, pressure, and salinity, which can affect the quality and reliability of the communication [107].

- Limited bandwidth: the available bandwidth for underwater communication is generally limited, which can affect the capacity and quality of the communication [107].
- Latency: underwater communication technologies can have high latency due to the slow speed of sound in water, which can be a challenge for applications that require real-time communication [107].

9. Applications of Tactile Internet

There is a large number of applications of the TI [108]. In this section, the uses of TI in healthcare and teleoperations are discussed. In general, a generalized architecture of the wireless TI system enabling the haptic communication feature is illustrated in Figure 3.

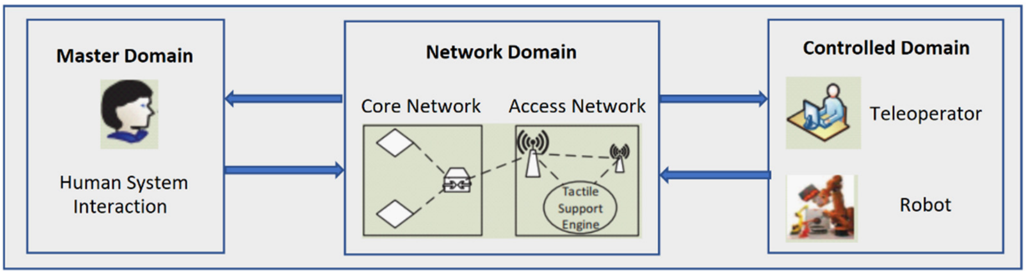

Figure 3. A generalized architecture of the wireless tactile internet system.

9.1. Healthcare

In [109], the author debated on the use cases of haptic applications in healthcare and their technical requirements by using robotic platforms to obtain the ultra-low latency communications over the 5G mobile systems. They first discussed the key feature of the architecture and enabling technology of the mobile system to obtain the ultra-low latency and reliability for many other use cases of healthcare applications such as wireless telesurgery and wireless service robots. In this paper, they proposed a solution for the new technology of the 5G mobile system. This work focused on the wide-ranging analysis of business models to deal with the costs and revenues of operators of robotics and healthcare with the 5G mobile systems.

In [110], the study on the 5G mobile system trends and technology and their influence on the Health and other IoT applications. Firstly, they highlight the preference requirements on the base of 1G mobile communications to 5G networks. This work focused to obtain the ultra-low latency and higher data rates under several new preference requirements. In this paper, they presented a technical survey on the 5G networks and deliberated the impression of the haptic application of healthcare and IoT on these movements.

This work [111] focused on the optimal haptic communication over the nanonetworks of the 5G mobile system for healthcare applications. Firstly, they proposed a system model over the nanonetwork for healthcare applications. They highlighted a problem for optimal communication over the nanonetworks. They presented a stochastic optimization framework and discussed their results by stochastic optimization. They divided this problem into an energy harvesting problem, packet dropping problem and resource allocation problem based on time availability. This work proposed an algorithm that deals with the parameters of the optimization problems. This work shows that for obtaining the optimal communication the molecular communication is better significant in both the energy and potential for real-time applications of healthcare over the nanonetworks under the TI.

In [112], the authors presented a case study in the domain of 5G mobile networks of healthcare and the internet of skills. They focused on the telesurgery inspiration and models with the use of robots. This work presented prototyping of the telesurgery and the perception of sensory over the 5G network. They presented the Software Defined Network (SDN) model and the architecture parameters. This work highlights the experimental arrangements and discussed the performance parameters. This work shows that for the real-life problems of teleoperation, better practice is compulsory for requirement of the better quality and SDN features for the internet of skills over the 5G mobile networks.

In [113], the authors discussed a study on the 5G mobile network with the interaction of humans and machines in the modern era of the medical field. First, they presented the telesurgery technique and the system architecture of the telesurgery for the human-machine interaction over the 5G mobile network. Finally, this work highlights the optimization of human-machine interaction and the open challenges in the field of telesurgery as in the aspects of ultra-high reliability. This work shows that the communication and protocols must be highlighted for better understanding of telesurgery in the modern medical diagnoses and find better results with the help of robotic surgery.

In [67], the authors model the approaches and their challenges of the haptic-mediated for enhancement of the sustained attention and their influences on the daily life human activities. This paper highlights the issues that occur with the association with the expansion of novel approaches to haptic technology. First, they discussed the sustained attention and the potential influence of the training and they discussed the nonhaptic attention-training approaches. This work focused on the featured and the classification of existing haptic-mediated attention-training. They mainly discussed the effects of haptic perception on the attention training and proposed a novel application for the challenging issues accompanying the haptic technologies. This work shows that attention control directly depends on the training of attention. This work shows that it is very cooperative in several specialized attention-demanding pitches of the real-life scenarios.

9.2. Telesurgery

In [48], the authors provide a discussion on the TI architecture, requirements and their services over the 5G mobile network. This work highlights the open challenges for haptic communication and the ultra-low latency and reliability of the 5G networks over the TI. This paperwork provides an overview and the capabilities of the Fifth Generation (5G) system for the services of the TI. They discuss a work of the 5G radio network design and the requirements (capabilities) for achieving the ultra-low latency and high reliability. The service of the TI is end-to-end provisioned, this work also provides the use cases of the teleoperations as an example for the end-to-end latency provisioned.

In [114], the authors discuss the complete overview in the form of architectures, requirements and the application of the 5G enabled mobile network TI. This work focused on the ultra-low latency and ultra-high reliability over the 5G mobile networks. First, they highlight the different domains of TI applications, e.g., in medical operations, industries and virtual reality and augmented reality. This work presents the technical key requirements for the comprehension of the TI. Furthermore, they discussed the end-to-end architecture model characteristics and their domains for the TI. This work produces more opportunities in the modern era to serve society, e.g., in the domains of medical and business and provide benefits to solve the upcoming challenges.

In [115], the authors grant the argument towards the 6G mobile network and deliver a wide-ranging impression on the next generation 6G. Firstly, this paperwork provides a summary of the emerging trends that helps to understand the future generation mobile network and the vital characteristics to develop the forthcoming 6G mobile networks. They provide the use case study over the 6G mobile network in Finland and present a comprehensive discussion on the different domains such as research, business and society from this time to the next upcoming decades. They also highlight the strengths, weakness, opportunities and the threats and presents a comparison between the current 5G and the forthcoming next generation. This work shows the discussion on the 5G and the next generation and motivates for the upcoming 6G challenges.

In [116], the authors present a survey on several haptic devices and discuss the capabilities and the feedback knowledge of haptic devices for mobile augmented reality (MAR). First, this work highlights the current challenging issues in the field of human-machine interaction and for haptic devices. Furthermore, they categorize the haptic devices based on haptic feedback senses into groups. This paperwork focused on the wearable haptic devices for MAR and discussed the design principles of the wearable haptic. Their work demonstrates the future direction and the upcoming challenges issues of wearable haptic devices. This work shows that it can help to better understand the working and the challenging issues that can be faced in the future and provide a solution for the upcoming issues of the haptic feedback for wearable haptic devices in the domain of MAR.

In [66], authors discuss the enabled VR open challenges and the prospects for the TI. First, they highlight the video streaming protocols and the services of the VR. This research work is focused on condensing the end-to-end latency of wireless networks for the TI. They highlight the open research challenges of the wireless networks in the field of VR video streaming. Mobile edge computing (MEC), optimization of transport and application protocols and multi-modal integration and quality control and experimental procedures for VR and haptic communication are the current challenging issues. This paper helps to better understand the challenges and provides a key for new opportunities.

In [85], the authors discussed the haptic rendering and the stability of virtual reality objects. Firstly, they discuss the interaction between human and machines and the haptic device's interaction with the virtual reality. The purpose of this research work is to provide a realistic simulation of virtual reality. In this research work, they use the force control and the position control for the interface of haptic devices. They work on the energy-compensating controller (ECC) to avoid the instability produced by the leakage of energy. ECC provides high stability in the haptic rendering and the threshold instability also increases. They sued a fuzzy impedance controller to attain the threshold stability and to control the robot stiffness. This work shows that ECC and fuzzy impedance, both are used for achieving the stability in position control of the haptic rendering for virtual reality objects. The haptic interaction in the presence of an energy-computing controller is shown in Figure 4.

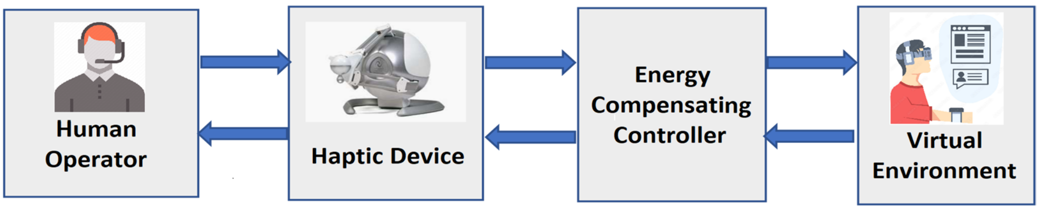

Figure 4. Haptic interaction in the presence of energy computing controller.

In [117], the authors present a study on the characteristics, data transmission latency and the system model of the teleoperation. The main purpose of this paper is to achieve the ultra-low latency and ultra-high reliability and stability of the communication between the controlled operator and the remote object. For this purpose, they proposed a novel solution of soft resource reservation to reduce the communication delay of teleoperation over the mobile networks. They discuss the communication delay between the master and the slave devices and the round-trip communication route over the single haptic devices and the multiple haptic devices. The debate on the analysis of the 5G mobile network and the shorter transmit time interval. This work shows that to achieve the stability of the teleoperations, the proposed mechanism is very useful for reducing the communication delay between the controlled and remote devices.

In [118], the dynamic control scheme for teleoperations to increase the quality-of-experience for variable-length communication delay is presented. To perform this task, a novel scheme for the haptic data reduction to control the variable-length delay is achieved by dynamic control scheme switching and enhancing quality-of-experience. Moreover, this work also highlights the intrinsic relationship between human perceptions for time-delayed operations.

9.3. Autonomous Driving

Self-driving vehicles and vehicle platooning are being explored as the next step in modern transportation. Such technologies rely highly on the Tactile Internet, which enables communication between vehicles in a range of areas, in order to reduce accidents and traffic jams on the roads [119]. In today's urban environments, where roads are often congested, self-driving vehicles could significantly reduce travel time. They also improve safety, as a moment of human negligence can lead to an accident due to the short amount of time it takes for an impact to occur. To achieve fully autonomous driving, which is necessary for changing traffic behavior, it is crucial to have high reliability, adaptability, and support for dynamic communication in future remote systems [120].

9.4. Virtual and Augmented Reality

The Tactile Internet, which allows for communication among devices, can improve the user experience of virtual and augmented reality applications. In virtual reality, users can interact with a shared, haptic virtual environment and perceive the sound and touch of objects [121]. In augmented reality, a combination of real and computer-generated content is displayed in the user's field of view, and the ability to touch and feel virtual objects allows for a range of applications that require a high level of accuracy [122].

The accuracy of the connection between users and the virtual simulation, even when there is a delay of a few milliseconds, is crucial for the effectiveness of augmented reality applications such as driver assistance systems and training. The Tactile Internet allows for the dynamic integration of additional data into a user's field of view, enabling the detection and avoidance of potential hazards. Virtual reality headsets for gaming are gaining popularity, particularly among younger users, but the low latency of the current Internet has limited the development of more advanced applications. The Tactile Internet can address these limitations by facilitating real-time communication and gameplay between dynamic players and enabling greater freedom in a variety of games [123].

9.5. Industrial Automation

Automation is becoming more widespread in various industries, especially manufacturing, and is a key area of application for the Tactile Internet. For example, in industrial sensors, the response time of fast-moving control circuits is typically less than 1 ms. These systems require various levels of latency, data rate, reliability, and security. High-speed wired connections such as modern Ethernet can support control actions. In the future, complex connected machinery and systems will need to be largely or fully remotely controlled to enable flexibility in production. This requires a consistent level of quality and minimal latency from start to finish, which can be achieved more easily using the Tactile Internet [124,125].

10. Enabling Haptic Communication over 6G Mobile Networks

Due to increased bandwidth requirements of haptic communication, specialized and dedicated equipment is required which can entertain throughput, latency requirements of such communication [126,127]. However, this specialized equipment is often not readily available in remote or rural areas. To set up, such equipment requires more time [128]. On the contrary, mobile networks are much easier to deploy and can also handle haptic information. This handling becomes realizable by using 6G networks because 6G will be more technically optimized than 5G in terms of latency, throughput, etc. This optimization opens door to new challenges [129,130].

To define new standards for 6G communication, modifications are underway in already ongoing 5G concepts. In this regard, 3GPP has already developed specifications for 5G in its releases 15,16 and 17 and has submitted its working to ITU [131–135]. Now it has started working on release 18 which aims at developing different methodologies for 6G networks. This will allow transformation from 5G networks to 6G networks. Two new areas which are defined by 3GPP and ITU are massive machine type communication and critical machine type communication [10,136–138]. One of the major parameters in any network is round trip time (RTT). With the advancement of mobile networks generations, the value of this parameter is reduced. This improvement in RTT helps meet the latency requirements of haptic communication [139]. Table 1 shows values of RTT [140,141] along with other important key point indicators (KPIs) related to different generations. The detailed comparison of different performance parameters is discussed in Table 2.

Table 2. Performance evaluation comparison of different parameters.

Ref.	Methodology	Round-Trip Latency	Energy Efficiency	Security
[74]	ETCC of MAS	✓	✗	✗
[75]	Adopt optical transport for backhaul medium and increasing computational power of nodes	✓	✗	✗
[76]	Computation on multi-level clouds	✓	✗	✗
[77]	Increase in bandwidth or by shifting the computations from the core network controller to the mini-cloud unit	✓	✓	✗
[69]	Computation on multi-level clouds	✓	✓	✓
[78]	Computation on network cloud	✓	✗	✗
[81]	Multi-level mobile edge computing	✓	✗	✗
[82]	Adjustment of queuing delays in between TI users using SCA and DC	✗	✓	✗
[83]	Resource allocation (RA) using admission control (AC) for TI users in C-RAN network	✓	✗	✗

11. Issues and Challenges of Tactile Internet over 6G

TI is an enabling technology in the field of 6G and holds much potential for future research [142,143]. In order to make this technology a reality, various research challenges must be dealt with [144]. The primary challenge faced by 5G networks that makes it difficult to facilitate these services was the large-scale integration of small cells into existing mobile communications infrastructure. These highly localized, low-power nodes are required to ensure high levels of reliability and performance during peak traffic times. Furthermore, in order for 6G networks to enable URLLC, mMTC and eMBB service quality must be optimized through intelligent network slicing techniques that dynamically allocate resources based on user needs [145]. Sixth-generation (6G) networks remedy many of these issues with a new technology paradigm known as network-as-a-service (NaaS). This framework allows for a single radio access network to provide different slices tailored towards specific use cases such as URLLC, mMTC or eMBB without compromising reliability or performance while still reducing energy consumption and increasing throughput capabilities significantly compared to 5G networks. Additionally, 6G networks have an increased focus on enabling secure machine learning applications which helps improve overall intelligence within the system while mitigating security concerns associated with the introduction of AI technologies into modern wireless systems [146]. Finally, 6G aims to utilize multiple spectrum bands more effectively than before by allowing both licensed spectrum users and unlicensed spectrum consumers coexist harmoniously thereby greatly improving coverage area and enhancing corresponding data speeds resulting from shared utilization between several frequencies seamlessly with minimal overlap interference issues or delay periods when transitioning from one band/slice setup to another depending on current user load capacity requirements [147]. Below we discuss some of the challenges.

11.1. Protocol Design

While still in its initial stage, TI has a lot of room for efficient protocol design. This efficiency is achieved by designing a protocol that focuses on latency reduction. Few works have been performed in this regard. Consequently, in [148], an advanced 5G-TCP algorithm is designed which achieves low latency and high data rate up to 400 Gb/sec. This algorithm deals with congestion avoidance of backhaul traffic. However, this algorithm runs inside a kernel which may cause interference issues with other applications and can maximize latency. Therefore, another research direction is to develop application-specific protocols that run on user space instead of kernel space. In [149], such application-specific transport protocol is developed for vehicular networks. In this work, low latency is achieved.

11.2. Data Compaction

Bandwidth limitation is a crucial aspect of TI [150]. To offer a better user experience of haptic communication, efficient data compression techniques are required. For this purpose, efficient haptic codecs are designed incorporating both kinesthetic and tactile learning [151,152]. Various data compression techniques for transmitting kinesthetic information over the network are proposed in the literature, e.g., in [153], real-time codec and delayed codec techniques are discussed.

11.3. Haptic Devices

Haptic devices consist of sensors and actuators. These receive physical input from a user, which is relayed to end device at haptic actuators. These sensors work on the basic principle of pressure sensing. This sensing mechanism is either capacitive or resistive [154,155]. These haptic devices are still in their developing phase. Issues related to cost, size of hardware sensitivity, sensing time, etc., are still of major concern. Moreover, these devices should also be able to handle both kinesthetic, e.g., touch, vibration sensing, etc. and cutaneous sensations, e.g., movement of muscle, etc. [156–158]. In this regard, the authors in [159] develop an actuator based on electroactive polymer which creates vibrations suitable enough to be sensed by end-users. Similarly, in [160], the hardware is developed for smartphones that produce sensations of kissing similar to reality. More research directions for better sensor design may include optimized circuit design, range of operation, degree of freedom as well as durability.

11.4. High Accuracy

One of the main challenges that may be faced in TI-based communication is how accurately information is transmitted [161]. It is dependent upon many parameters such as type of interface between end-users, transmit time and response time [162]. For information to be reliable, some kind of feedback is needed. This feedback is carried out by TCP at the transport layer. However, by using this protocol, response time is compromised over the quality of information between end users. Therefore, one research direction can be used to modify the working of the transport layer such that quality and response time are greatly impacted by one another. Other issues include modifying data frames for IPV6 based networks as small as possible so that there is always low latency [75].

11.5. Multi-Model Sensory Information

In TI-based systems, in addition to haptic information, audio and visual information for better emotive experience can also be needed [163]. However, to integrate these three sensory behaviors, some type of synchronization is necessary in terms of different parameter requirement [164]. These parameters include but are not limited to sampling rate, transmission rate, etc. Some kind of technique is needed so that haptic, visual and audio information is simultaneously multiplexed keeping because of the above-mentioned parameters. Refs. [75,165] have carried out such multiplexing technique at the application layer but more work can be exploited by designing a cognitive multiplexing technique in different wireless environments. The 6G network capabilities are determined by the requirements of the use cases which will need to utilize effectively the network. Essentially, we need to iterate through the use cases and extract those requirements.

12. Conclusions

In conclusion, this research paper provides a comprehensive overview of the issues and challenges associated with enabling haptic communication over Tactile Internet. The study explores the various features required for haptic communication over TI, such as ultra-low latency, security, and energy efficiency. Methodologies and technologies that can facilitate haptic communication are discussed, including frameworks, features, and existing research works in the field. The findings are summarized, highlighting the performance evaluation parameters in Table 2. The growing demand for multimedia services and device proliferation has led to limited radio resources, posing challenges in efficiently allocating them for D2D-assisted haptic communications. The jlioint optimization of uplink and downlink resource configuration can minimize bandwidth usage, and D2D connectivity is crucial for enhancing cellular network efficiency in the 5G era. Backscatter communications (BsC) and non-orthogonal multiple access (NOMA) offer energy efficiency and capacity improvements. The research emphasizes the need for a novel infrastructure with low latency and high precision to meet the demands of potential communication services. Unmanned aerial vehicles (UAVs) have the potential to deliver ultra-low latency services to remote areas, while software-defined 5G/6G networks and network slicing provide flexibility and meet diverse network demands. Exploring wireless communication beyond 100 GHz and THz levels shows promise for future applications. Emotion detection and communication systems, along with optimized VR video streaming solutions, contribute to enhanced human-machine interaction. The research underscores the importance of addressing security risks, developing efficient multiple access methods, enabling emotion communication, optimizing application migration, and embracing the Internet of Skills. Proposed frameworks and approaches address latency reduction, resource allocation optimization, and network congestion minimization. Leveraging software-defined networks, edge computing, and multi-level cloud-based systems enhances the efficiency of haptic communication systems. Anticipated 6G networks aim to incorporate aerial, ground, and underwater communication technologies, each with its own advantages and challenges. Aerial communication offers wide coverage and high speed but faces interference, limited bandwidth, weather, security, and energy efficiency challenges. Ground communication provides reliability and low latency but has limitations in coverage, flexibility, cost, vulnerability to physical damage, and mobility. Underwater communication offers security and high data rates but faces challenges related to coverage, complexity, cost, environmental factors, bandwidth, and latency. The paper emphasizes the need for specialized equipment to meet the bandwidth and latency requirements of haptic communication, particularly in remote areas. However, 6G networks are expected to be more optimized, capable of handling haptic information with lower latency and higher throughput. Ongoing efforts focus on developing new standards for 6G communication, including massive machine type communication and critical machine type communication. Additionally, the paper highlights various challenges such as protocol design for latency reduction, data compaction techniques, advancements in haptic devices, accurate information transmission, and synchronization of multi-modal sensory information. Overall, this research contributes to the understanding of haptic communication in the context of 6G networks and provides insights into potential solutions for addressing the associated challenges.

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References

1. You, X.; Wang, C.-X.; Huang, J.; Gao, X.; Zhang, Z.; Wang, M.; Huang, Y.; Zhang, C.; Jiang, Y.; Wang, J. Towards 6G Wireless Communication Networks: Vision, Enabling Technologies, and New Paradigm Shifts. *Sci. China Inf. Sci.* **2021**, *64*, 110301. [CrossRef]
2. Weon, I.-S.; Lee, S.-G. Intelligent Robotic Walker with Actively Controlled Human Interaction. *ETRI J.* **2018**, *40*, 522–530. [CrossRef]
3. Alam, M.M.; Malik, H.; Khan, M.I.; Pardy, T.; Kuusik, A.; Le Moullec, Y. A Survey on the Roles of Communication Technologies in IoT-Based Personalized Healthcare Applications. *IEEE Access* **2018**, *6*, 36611–36631. [CrossRef]
4. Gómez-Barroso, J.L.; Marbán-Flores, R. Telecommunications and Economic Development–The 21st Century: Making the Evidence Stronger. *Telecommun. Policy* **2020**, *44*, 101905. [CrossRef]
5. Kousalya, K.; Mohana, R.S.; Sasipriyaa, N.; Prabha, C.; Udhayakumar, T. 6G with Smart Healthcare, Haptic Communication: An Overall Perspective. In *Handbook of Research on Design, Deployment, Automation, and Testing Strategies for 6G Mobile Core Network*; IGI Global: Hershey, PA, USA, 2022; pp. 267–283.
6. Gulati, K.; Boddu, R.S.K.; Kapila, D.; Bangare, S.L.; Chandnani, N.; Saravanan, G. A Review Paper on Wireless Sensor Network Techniques in Internet of Things (IoT). *Mater. Today: Proc.* **2022**, *51*, 161–165. [CrossRef]
7. Koohang, A.; Sargent, C.S.; Nord, J.H.; Paliszkiewicz, J. Internet of Things (IoT): From Awareness to Continued Use. *Int. J. Inf. Manag.* **2022**, *62*, 102442. [CrossRef]
8. Atzori, L.; Iera, A.; Morabito, G. The Internet of Things: A Survey. *Comput. Netw.* **2010**, *54*, 2787–2805. [CrossRef]
9. Oğur, N.B.; Al-Hubaishi, M.; Çeken, C. IoT Data Analytics Architecture for Smart Healthcare Using RFID and WSN. *ETRI J.* **2022**, *44*, 135–146. [CrossRef]
10. Antonakoglou, K.; Xu, X.; Steinbach, E.; Mahmoodi, T.; Dohler, M. Toward Haptic Communications over the 5G Tactile Internet. *IEEE Commun. Surv. Tutor.* **2018**, *20*, 3034–3059. [CrossRef]
11. Raisamo, R.; Salminen, K.; Rantala, J.; Farooq, A.; Ziat, M. Interpersonal Haptic Communication: Review and Directions for the Future. *Int. J. Hum.-Comput. Stud.* **2022**, *166*, 102881. [CrossRef]
12. Qiao, Y.; Zheng, Q.; Lin, Y.; Fang, Y.; Xu, Y.; Zhao, T. Haptic Communication: Toward 5G Tactile Internet. In Proceedings of the 2020 Cross Strait Radio Science & Wireless Technology Conference (CSRSWTC), Fuzhou, China, 13–16 December 2020; pp. 1–3.
13. Ranjha, A.; Kaddoum, G.; Rahim, M.; Dev, K. URLLC in UAV-Enabled Multicasting Systems: A Dual Time and Energy Minimization Problem Using UAV Speed, Altitude and Beamwidth. *Comput. Commun.* **2022**, *187*, 125–133. [CrossRef]
14. Narsani, H.K.; Ranjha, A.; Dev, K.; Memon, F.H.; Qureshi, N.M.F. Leveraging UAV-Assisted Communications to Improve Secrecy for URLLC in 6G Systems. *Digit. Commun. Netw.* **2022**, *in press*. [CrossRef]
15. Rao, J.; Vrzic, S. Packet Duplication for URLLC in 5G: Architectural Enhancements and Performance Analysis. *IEEE Netw.* **2018**, *32*, 32–40. [CrossRef]
16. Dai, H.; Wang, Y.; Zhou, T.; Yang, L. Joint Service Improvement and Content Placement for Cache-Enabled Heterogeneous Cellular Networks. *IET Signal Process.* **2019**, *13*, 253–261. [CrossRef]
17. Azari, A.; Ozger, M.; Cavdar, C. Risk-Aware Resource Allocation for URLLC: Challenges and Strategies with Machine Learning. *IEEE Commun. Mag.* **2019**, *57*, 42–48. [CrossRef]
18. Popovski, P.; Stefanović, Č.; Nielsen, J.J.; De Carvalho, E.; Angjelichinoski, M.; Trillingsgaard, K.F.; Bana, A.-S. Wireless Access in Ultra-Reliable Low-Latency Communication (URLLC). *IEEE Trans. Commun.* **2019**, *67*, 5783–5801. [CrossRef]
19. Bhat, J.R.; Alqahtani, S.A. 6G Ecosystem: Current Status and Future Perspective. *IEEE Access* **2021**, *9*, 43134–43167. [CrossRef]
20. Salah, I.; Mabrook, M.M.; Hussein, A.I.; Rahouma, K.H. Comparative Study of Efficiency Enhancement Technologies in 5G Networks-A Survey. *Procedia Comput. Sci.* **2021**, *182*, 150–158. [CrossRef]
21. Slalmi, A.; Chaibi, H.; Chehri, A.; Saadane, R.; Jeon, G.; Hakem, N. On the Ultra-Reliable and Low-Latency Communications for Tactile Internet in 5G Era. *Procedia Comput. Sci.* **2020**, *176*, 3853–3862. [CrossRef]
22. Ateya, A.A.; Muthanna, A.; Makolkina, M.; Koucheryavy, A. Study of 5G Services Standardization: Specifications and Requirements. In Proceedings of the 2018 10th International Congress on Ultra Modern Telecommunications and Control Systems and Workshops (ICUMT), Moscow, Russia, 5–9 November 2018; pp. 1–6.
23. Park, J.H.; Rathore, S.; Singh, S.K.; Salim, M.M.; Azzaoui, A.E.; Kim, T.W.; Pan, Y.; Park, J.H. A Comprehensive Survey on Core Technologies and Services for 5G Security: Taxonomies, Issues, and Solutions. *Hum.-Centric Comput. Inf. Sci* **2021**, *11*. [CrossRef]
24. Wijethilaka, S.; Liyanage, M. Survey on Network Slicing for Internet of Things Realization in 5G Networks. *IEEE Commun. Surv. Tutor.* **2021**, *23*, 957–994. [CrossRef]
25. Mazied, E.A.; Liu, L.; Midkiff, S.F. Towards Intelligent RAN Slicing for B5G: Opportunities and Challenges. *arXiv* **2021**, arXiv:2103.00227.
26. Wei, F.; Feng, G.; Sun, Y.; Wang, Y.; Qin, S.; Liang, Y.-C. Network Slice Reconfiguration by Exploiting Deep Reinforcement Learning with Large Action Space. *IEEE Trans. Netw. Serv. Manag.* **2020**, *17*, 2197–2211. [CrossRef]
27. Thiruvasagam, P.K.; Chakraborty, A.; Murthy, C.S.R. Resilient and Latency-Aware Orchestration of Network Slices Using Multi-Connectivity in MEC-Enabled 5G Networks. *IEEE Trans. Netw. Serv. Manag.* **2021**, *18*, 2502–2514. [CrossRef]

28. Giordani, M.; Polese, M.; Mezzavilla, M.; Rangan, S.; Zorzi, M. Toward 6G Networks: Use Cases and Technologies. *IEEE Commun. Mag.* **2020**, *58*, 55–61. [CrossRef]
29. Mucchi, L.; Jayousi, S.; Caputo, S.; Paoletti, E.; Zoppi, P.; Geli, S.; Dioniso, P. How 6G Technology Can Change the Future Wireless Healthcare. In Proceedings of the 2020 2nd 6G wireless summit (6G SUMMIT), Levi, Finland, 17–20 March 2020; pp. 1–6.
30. Suraci, C.; De Angelis, V.; Lofaro, G.; Giudice, M.L.; Marrara, G.; Rinaldi, F.; Russo, A.; Bevacqua, M.T.; Lax, G.; Mammone, N. The Next Generation of EHealth: A Multidisciplinary Survey. *IEEE Access* **2022**, *10*, 134623–134646. [CrossRef]
31. De Alwis, C.; Pham, Q.-V.; Liyanage, M. *6G Frontiers: Towards Future Wireless Systems*; John Wiley & Sons: Hoboken, NJ, USA, 2022.
32. Jiang, W.; Han, B.; Habibi, M.A.; Schotten, H.D. The Road towards 6G: A Comprehensive Survey. *IEEE Open J. Commun. Soc.* **2021**, *2*, 334–366. [CrossRef]
33. Tataria, H.; Shafi, M.; Molisch, A.F.; Dohler, M.; Sjöland, H.; Tufvesson, F. 6G Wireless Systems: Vision, Requirements, Challenges, Insights, and Opportunities. *Proc. IEEE* **2021**, *109*, 1166–1199. [CrossRef]
34. Mahmood, M.R.; Matin, M.A. Enabling Technologies for Internet of Everything. In *Enabling Technologies for Next Generation Wireless Communications*; CRC Press: Boca Raton, FL, USA, 2020; pp. 33–43.
35. Gavrilovska, L.; Rakovic, V.; Denkovski, D. From Cloud RAN to Open RAN. *Wirel. Pers. Commun.* **2020**, *113*, 1523–1539. [CrossRef]
36. Calvanese Strinati, E.; Barbarossa, S.; Choi, T.; Pietrabissa, A.; Giuseppi, A.; De Santis, E.; Vidal, J.; Becvar, Z.; Haustein, T.; Cassiau, N. 6G in the Sky: On-Demand Intelligence at the Edge of 3D Networks. *ETRI J.* **2020**, *42*, 643–657. [CrossRef]
37. Ali-Yahiya, T.; Monnet, W. *The Tactile Internet*; John Wiley & Sons: Hoboken, NJ, USA, 2022.
38. Lacalle, I.; López, C.; Vaño, R.; Palau, C.E.; Esteve, M.; Ganzha, M.; Paprzycki, M.; Szmeja, P. Tactile Internet in Internet of Things Ecosystems. In *International Conference on Electrical and Electronics Engineering*; Springer: Berlin/Heidelberg, Germany, 2022; pp. 794–807.
39. Promwongsa, N.; Ebrahimzadeh, A.; Naboulsi, D.; Kianpisheh, S.; Belqasmi, F.; Glitho, R.; Crespi, N.; Alfandi, O. A Comprehensive Survey of the Tactile Internet: State-of-the-Art and Research Directions. *IEEE Commun. Surv. Tutor.* **2020**, *23*, 472–523. [CrossRef]
40. Fettweis, G.P.; Boche, H. 6G: The Personal Tactile Internet—And Open Questions for Information Theory. *IEEE BITS Inf. Theory Mag.* **2021**, *1*, 71–82. [CrossRef]
41. Padhi, P.K.; Charrua-Santos, F. 6G Enabled Tactile Internet and Cognitive Internet of Healthcare Everything: Towards a Theoretical Framework. *Appl. Syst. Innov.* **2021**, *4*, 66. [CrossRef]
42. Gupta, R.; Tanwar, S.; Tyagi, S.; Kumar, N. Tactile Internet and Its Applications in 5G Era: A Comprehensive Review. *Int. J. Commun. Syst.* **2019**, *32*, e3981. [CrossRef]
43. Aijaz, A.; Sooriyabandara, M. The Tactile Internet for Industries: A Review. *Proc. IEEE* **2018**, *107*, 414–435. [CrossRef]
44. Mourtzis, D.; Angelopoulos, J.; Panopoulos, N. Smart Manufacturing and Tactile Internet Based on 5G in Industry 4.0: Challenges, Applications and New Trends. *Electronics* **2021**, *10*, 3175. [CrossRef]
45. Zubair Islam, M.; Ali, R.; Haider, A.; Kim, H.S. Reinforcement Learning-Aided Edge Intelligence Framework for Delay-Sensitive Industrial Applications. *Sensors* **2022**, *22*, 8001. [CrossRef]
46. Ivanova, E.; Eden, J.; Zhu, S.; Carboni, G.; Yurkewich, A.; Burdet, E. Short Time Delay Does Not Hinder Haptic Communication Benefits. *IEEE Trans. Haptics* **2021**, *14*, 322–327. [CrossRef]
47. Kim, K.S.; Kim, D.K.; Chae, C.-B.; Choi, S.; Ko, Y.-C.; Kim, J.; Lim, Y.-G.; Yang, M.; Kim, S.; Lim, B. Ultrareliable and Low-Latency Communication Techniques for Tactile Internet Services. *Proc. IEEE* **2018**, *107*, 376–393. [CrossRef]
48. Sachs, J.; Andersson, L.A.; Araújo, J.; Curescu, C.; Lundsjö, J.; Rune, G.; Steinbach, E.; Wikström, G. Adaptive 5G Low-Latency Communication for Tactile Internet Services. *Proc. IEEE* **2018**, *107*, 325–349. [CrossRef]
49. Fanibhare, V.; Sarkar, N.I.; Al-Anbuky, A. A Survey of the Tactile Internet: Design Issues and Challenges, Applications, and Future Directions. *Electronics* **2021**, *10*, 2171. [CrossRef]
50. Banafaa, M.; Shayea, I.; Din, J.; Azmi, M.H.; Alashbi, A.; Daradkeh, Y.I.; Alhammadi, A. 6G Mobile Communication Technology: Requirements, Targets, Applications, Challenges, Advantages, and Opportunities. *Alex. Eng. J.* **2022**, *64*, 245–274. [CrossRef]
51. Jameel, F.; Hamid, Z.; Jabeen, F.; Zeadally, S.; Javed, M.A. A Survey of Device-to-Device Communications: Research Issues and Challenges. *IEEE Commun. Surv. Tutor.* **2018**, *20*, 2133–2168. [CrossRef]
52. She, C.; Yang, C.; Quek, T.Q. Joint Uplink and Downlink Resource Configuration for Ultra-Reliable and Low-Latency Communications. *IEEE Trans. Commun.* **2018**, *66*, 2266–2280. [CrossRef]
53. Amodu, O.A.; Othman, M.; Noordin, N.K.; Ahmad, I. A Primer on Design Aspects, Recent Advances, and Challenges in Cellular Device-to-Device Communication. *Ad Hoc Networks* **2019**, *94*, 101938. [CrossRef]
54. Asif, M.; Ihsan, A.; Khan, W.U.; Ranjha, A.; Zhang, S.; Wu, S.X. Energy-Efficient Backscatter-Assisted Coded Cooperative-NOMA for B5G Wireless Communications. *IEEE Trans. Green Commun. Netw.* **2022**, *7*, 70–83. [CrossRef]
55. Yastrebova, A.; Kirichek, R.; Koucheryavy, Y.; Borodin, A.; Koucheryavy, A. Future Networks 2030: Architecture & Requirements. In Proceedings of the 2018 10th International Congress on Ultra Modern Telecommunications and Control Systems and Workshops (ICUMT), Moscow, Russia, 5–9 November 2018; pp. 1–8.
56. Long, Q.; Chen, Y.; Zhang, H.; Lei, X. Software Defined 5G and 6G Networks: A Survey. *Mob. Netw. Appl.* **2019**, *27*, 1792–1812. [CrossRef]

57. Aijaz, A. Towards 5G-Enabled Tactile Internet: Radio Resource Allocation for Haptic Communications. In Proceedings of the 2016 IEEE Wireless Communications and Networking Conference Workshops (WCNCW), Doha, Qatar, 3–6 April 2016; pp. 145–150.
58. Aijaz, A. A Radio Resource Slicing Framework for 5G Networks With Haptic Communications. *IEEE Syst. J.* **2017**, *12*, 2285–2296. [CrossRef]
59. Aijaz, A. Toward Human-in-the-Loop Mobile Networks: A Radio Resource Allocation Perspective on Haptic Communications. *IEEE Trans. Wirel. Commun.* **2018**, *17*, 4493–4508. [CrossRef]
60. Rost, P.; Mannweiler, C.; Michalopoulos, D.S.; Sartori, C.; Sciancalepore, V.; Sastry, N.; Holland, O.; Tayade, S.; Han, B.; Bega, D. Network Slicing to Enable Scalability and Flexibility in 5G Mobile Networks. *IEEE Commun. Mag.* **2017**, *55*, 72–79. [CrossRef]
61. Rappaport, T.S.; Xing, Y.; Kanhere, O.; Ju, S.; Madanayake, A.; Mandal, S.; Alkhateeb, A.; Trichopoulos, G.C. Wireless Communications and Applications above 100 GHz: Opportunities and Challenges for 6G and Beyond. *IEEE Access* **2019**, *7*, 78729–78757. [CrossRef]
62. Nawaz, S.J.; Sharma, S.K.; Wyne, S.; Patwary, M.N.; Asaduzzaman, M. Quantum Machine Learning for 6G Communication Networks: State-of-the-Art and Vision for the Future. *IEEE Access* **2019**, *7*, 46317–46350. [CrossRef]
63. Xing, Y.; Rappaport, T.S. Propagation Measurement System and Approach at 140 GHz-Moving to 6G and above 100 GHz. In Proceedings of the 2018 IEEE Global Communications Conference (GLOBECOM), Abu Dhabi, United Arab Emirates, 9–13 December 2018; pp. 1–6.
64. Na, W.; Dao, N.-N.; Kim, J.; Ryu, E.-S.; Cho, S. Simulation and Measurement: Feasibility Study of Tactile Internet Applications for MmWave Virtual Reality. *ETRI J.* **2020**, *42*, 163–174. [CrossRef]
65. Chen, M.; Zhou, P.; Fortino, G. Emotion Communication System. *IEEE Access* **2016**, *5*, 326–337. [CrossRef]
66. Vega, M.T.; Mehmli, T.; van der Hooft, J.; Wauters, T.; De Turck, F. Enabling Virtual Reality for the Tactile Internet: Hurdles and Opportunities. In Proceedings of the 2018 14th International Conference on Network and Service Management (CNSM), Rome, Italy, 5–9 November 2018; pp. 378–383.
67. Wang, D.; Li, T.; Afzal, N.; Zhang, J.; Zhang, Y. Haptics-Mediated Approaches for Enhancing Sustained Attention: Framework and Challenges. *Sci. China Inf. Sci.* **2019**, *62*, 211101. [CrossRef]
68. Kantola, R. 6g Network Needs to Support Embedded Trust. In Proceedings of the 14th International Conference on Availability, Reliability and Security, Canterbury, UK, 26–29 August 2019; pp. 1–5.
69. Ateya, A.A.; Vybornova, A.; Samouylov, K.; Koucheryavy, A. System Model for Multi-Level Cloud Based Tactile Internet System. In *Wired/Wireless Internet Communication*; Springer: Berlin/Heidelberg, Germany, 2017; pp. 77–86.
70. Al-Eryani, Y.; Hossain, E. Delta-OMA (D-OMA): A New Method for Massive Multiple Access in 6G. *arXiv* **2019**, arXiv:1901.07100.
71. Braun, P.J.; Pandi, S.; Schmoll, R.-S.; Fitzek, F.H. On the Study and Deployment of Mobile Edge Cloud for Tactile Internet Using a 5G Gaming Application. In Proceedings of the 2017 14th IEEE Annual Consumer Communications & Networking Conference (CCNC), Las Vegas, NV, USA, 8–11 January 2017; pp. 154–159.
72. Dohler, M.; Mahmoodi, T.; Lema, M.A.; Condoluci, M.; Sardis, F.; Antonakoglou, K.; Aghvami, H. Internet of Skills, Where Robotics Meets AI, 5G and the Tactile Internet. In Proceedings of the 2017 European Conference on Networks and Communications (EuCNC), Oulu, Finland, 12–15 June 2017; pp. 1–5.
73. Fadhil, H.M.; Dawood, Z.O. Evolutionary Perspective of Mobile Communication Technologies. In Proceedings of the 2018 International Conference on Computer and Applications (ICCA), Beirut, Lebanon, 25–26 August 2018; pp. 80–84.
74. Yu, P.; Fischione, C.; Dimarogonas, D.V. Distributed Event-Triggered Communication and Control of Linear Multiagent Systems under Tactile Communication. *IEEE Trans. Autom. Control* **2018**, *63*, 3979–3985. [CrossRef]
75. Aijaz, A.; Dohler, M.; Aghvami, A.H.; Friderikos, V.; Frodigh, M. Realizing the Tactile Internet: Haptic Communications over next Generation 5G Cellular Networks. *IEEE Wirel. Commun.* **2016**, *24*, 82–89. [CrossRef]
76. Ateya, A.A.; Vybornova, A.; Kirichek, R.; Koucheryavy, A. Multilevel Cloud Based Tactile Internet System. In Proceedings of the 2017 19th International Conference on Advanced Communication Technology (ICACT), PyeongChang, Republic of Korea, 19–22 February 2017; pp. 105–110.
77. Ateya, A.A.; Muthanna, A.; Gudkova, I.; Vybornova, A.; Koucheryavy, A. Intelligent Core Network for Tactile Internet System. In Proceedings of the International Conference on Future Networks and Distributed Systems, New York, NY, USA, 19–20 July 2017; pp. 1–6.
78. Banchs, A.; Breitbach, M.; Costa, X.; Doetsch, U.; Redana, S.; Sartori, C.; Schotten, H. A Novel Radio Multiservice Adaptive Network Architecture for 5G Networks. In Proceedings of the 2015 IEEE 81st Vehicular Technology Conference (VTC Spring), Glasgow, UK, 11–14 May 2015; pp. 1–5.
79. Bojkovic, Z.S.; Bakmaz, B.M.; Bakmaz, M.R. Vision and Enabling Technologies of Tactile Internet Realization. In Proceedings of the 2017 13th International Conference on Advanced Technologies, Systems and Services in Telecommunications (^{TEL}SIKS), Nis, Serbia, 18–20 October 2017; pp. 113–118.
80. Ateya, A.A.; Muthanna, A.; Gudkova, I.; Abuarqoub, A.; Vybornova, A.; Koucheryavy, A. Development of Intelligent Core Network for Tactile Internet and Future Smart Systems. *J. Sens. Actuator Netw.* **2018**, *7*, 1. [CrossRef]
81. Van Den Berg, D.; Glans, R.; De Koning, D.; Kuipers, F.A.; Lugtenburg, J.; Polachan, K.; Venkata, P.T.; Singh, C.; Turkovic, B.; Van Wijk, B. Challenges in Haptic Communications over the Tactile Internet. *IEEE Access* **2017**, *5*, 23502–23518. [CrossRef]

82. Gholipoor, N.; Parsaeefard, S.; Javan, M.R.; Mokari, N.; Saeedi, H.; Pishro-Nik, H. Cloud-Based Queuing Model for Tactile Internet in next Generation of RAN. In Proceedings of the 2020 IEEE 91st Vehicular Technology Conference (VTC2020-Spring), Antwerp, Belgium, 25–28 May 2020; pp. 1–6.
83. Gholipoor, N.; Parsaeefard, S.; Javan, M.R.; Mokari, N.; Saeedi, H.; Pishro-Nik, H. Resource Management and Admission Control for Tactile Internet in Next Generation of Radio Access Network. *IEEE Access* **2020**, *8*, 136261–136277. [CrossRef]
84. Azmandian, M.; Hancock, M.; Benko, H.; Ofek, E.; Wilson, A.D. Haptic Retargeting: Dynamic Repurposing of Passive Haptics for Enhanced Virtual Reality Experiences. In Proceedings of the 2016 Chi Conference on Human Factors in Computing Systems, San Jose, CA, USA, 7–12 May 2016; pp. 1968–1979.
85. Amirkhani, S.; Bahadorian, B.; Nahvi, A.; Chaibakhsh, A. Stable Haptic Rendering in Interactive Virtual Control Laboratory. *Intell. Serv. Robot.* **2018**, *11*, 289–300. [CrossRef]
86. Chowdhury, M.Z.; Shahjalal, M.; Ahmed, S.; Jang, Y.M. 6G Wireless Communication Systems: Applications, Requirements, Technologies, Challenges, and Research Directions. *IEEE Open J. Commun. Soc.* **2020**, *1*, 957–975. [CrossRef]
87. Dao, N.-N.; Pham, Q.-V.; Tu, N.H.; Thanh, T.T.; Bao, V.N.Q.; Lakew, D.S.; Cho, S. Survey on Aerial Radio Access Networks: Toward a Comprehensive 6G Access Infrastructure. *IEEE Commun. Surv. Tutor.* **2021**, *23*, 1193–1225. [CrossRef]
88. Guo, H.; Li, J.; Liu, J.; Tian, N.; Kato, N. A Survey on Space-Air-Ground-Sea Integrated Network Security in 6G. *IEEE Commun. Surv. Tutor.* **2021**, *24*, 53–87. [CrossRef]
89. Tang, F.; Chen, X.; Zhao, M.; Kato, N. The Roadmap of Communication and Networking in 6G for the Metaverse. *IEEE Wirel. Commun.* **2022**, 1–15. [CrossRef]
90. Dang, S.; Amin, O.; Shihada, B.; Alouini, M.-S. What Should 6G Be? *Nat. Electron.* **2020**, *3*, 20–29. [CrossRef]
91. Chi, N.; Zhou, Y.; Wei, Y.; Hu, F. Visible Light Communication in 6G: Advances, Challenges, and Prospects. *IEEE Veh. Technol. Mag.* **2020**, *15*, 93–102. [CrossRef]
92. Zhao, Y.; Zhao, J.; Zhai, W.; Sun, S.; Niyato, D.; Lam, K.-Y. A Survey of 6G Wireless Communications: Emerging Technologies. In *Future of Information and Communication Conference*; Springer: Berlin/Heidelberg, Germany, 2021; pp. 150–170.
93. Yang, P.; Xiao, Y.; Xiao, M.; Li, S. 6G Wireless Communications: Vision and Potential Techniques. *IEEE Netw.* **2019**, *33*, 70–75. [CrossRef]
94. Zhao, Y.; Zhai, W.; Zhao, J.; Zhang, T.; Sun, S.; Niyato, D.; Lam, K.-Y. A Comprehensive Survey of 6g Wireless Communications. *arXiv* **2020**, arXiv:2101.03889.
95. Huang, C.; Hu, S.; Alexandropoulos, G.C.; Zappone, A.; Yuen, C.; Zhang, R.; Di Renzo, M.; Debbah, M. Holographic MIMO Surfaces for 6G Wireless Networks: Opportunities, Challenges, and Trends. *IEEE Wirel. Commun.* **2020**, *27*, 118–125. [CrossRef]
96. Yan, S.; Cao, X.; Liu, Z.; Liu, X. Interference Management in 6G Space and Terrestrial Integrated Networks: Challenges and Approaches. *Intell. Converg. Netw.* **2020**, *1*, 271–280. [CrossRef]
97. Elmeadawy, S.; Shubair, R.M. 6G Wireless Communications: Future Technologies and Research Challenges. In Proceedings of the 2019 international conference on electrical and computing technologies and applications (ICECTA), Ras Al Khaimah, United Arab Emirates, 19–21 November 2019; pp. 1–5.
98. Wang, Z.; Du, Y.; Wei, K.; Han, K.; Xu, X.; Wei, G.; Tong, W.; Zhu, P.; Ma, J.; Wang, J. Vision, Application Scenarios, and Key Technology Trends for 6G Mobile Communications. *Sci. China Inf. Sci.* **2022**, *65*, 151301. [CrossRef]
99. Yuan, Y.; Zhao, Y.; Zong, B.; Parolari, S. Potential Key Technologies for 6G Mobile Communications. *Sci. China Inf. Sci.* **2020**, *63*, 183301. [CrossRef]
100. Zhang, L.; Liang, Y.-C.; Niyato, D. 6G Visions: Mobile Ultra-Broadband, Super Internet-of-Things, and Artificial Intelligence. *China Commun.* **2019**, *16*, 1–14. [CrossRef]
101. Xiao, Z.; Han, Z.; Nallanathan, A.; Dobre, O.A.; Clerckx, B.; Choi, J.; He, C.; Tong, W. Antenna Array Enabled Space/Air/Ground Communications and Networking for 6G. *IEEE J. Sel. Areas Commun.* **2022**, *40*, 2773–2804. [CrossRef]
102. Li, R.; Zhao, Z.; Xu, X.; Ni, F.; Zhang, H. The Collective Advantage for Advancing Communications and Intelligence. *IEEE Wirel. Commun.* **2020**, *27*, 96–102. [CrossRef]
103. Huang, X.; Zhang, J.A.; Liu, R.P.; Guo, Y.J.; Hanzo, L. Airplane-Aided Integrated Networking for 6G Wireless: Will It Work? *IEEE Veh. Technol. Mag.* **2019**, *14*, 84–91. [CrossRef]
104. Nguyen, D.C.; Ding, M.; Pathirana, P.N.; Seneviratne, A.; Li, J.; Niyato, D.; Dobre, O.; Poor, H.V. 6G Internet of Things: A Comprehensive Survey. *IEEE Internet Things J.* **2021**, *9*, 359–383. [CrossRef]
105. Cui, H.; Zhang, J.; Geng, Y.; Xiao, Z.; Sun, T.; Zhang, N.; Liu, J.; Wu, Q.; Cao, X. Space-Air-Ground Integrated Network (SAGIN) for 6G: Requirements, Architecture and Challenges. *China Commun.* **2022**, *19*, 90–108. [CrossRef]
106. Higuchi, A.; Takeshita, E.; Hisano, D.; Inoue, Y.; Maruta, K.; Nishio, T.; Hara-Azumi, Y.; Nakayama, Y. Aquatic Fronthaul for Underwater-Ground Communication in 6G Mobile Communications. In Proceedings of the 2022 IEEE 95th Vehicular Technology Conference:(VTC2022-Spring), Helsinki, Finland, 25 August 2022; pp. 1–6.
107. Mohsan, S.A.H.; Khan, M.A.; Mazinani, A.; Alsharif, M.H.; Cho, H.-S. Enabling Underwater Wireless Power Transfer towards Sixth Generation (6G) Wireless Networks: Opportunities, Recent Advances, and Technical Challenges. *J. Mar. Sci. Eng.* **2022**, *10*, 1282. [CrossRef]
108. Bera, S.; Das, H.; Nayak, S.; Patgiri, R. Future Tactile Internet: Issues, Challenges and Applications. In Proceedings of the 2021 6th International Conference on Signal Processing, Computing and Control (ISPCC), Solan, India, 7–9 October 2021; pp. 625–630.

109. Soldani, D.; Fadini, F.; Rasanen, H.; Duran, J.; Niemela, T.; Chandramouli, D.; Hoglund, T.; Doppler, K.; Himanen, T.; Laiho, J. 5G Mobile Systems for Healthcare. In Proceedings of the 2017 IEEE 85th vehicular technology conference (VTC Spring), Sydney, NSW, Australia, 4–7 June 2017; pp. 1–5.
110. Brito, J.M.C. Trends in Wireless Communications towards 5G Networks—The Influence of e-Health and IoT Applications. In Proceedings of the 2016 International Multidisciplinary Conference on Computer and Energy Science (SpliTech), Split, Croatia, 13–15 July 2016; pp. 1–7.
111. Feng, L.; Ali, A.; Iqbal, M.; Bashir, A.K.; Hussain, S.A.; Pack, S. Optimal Haptic Communications over Nanonetworks for E-Health Systems. *IEEE Trans. Ind. Inform.* **2019**, *15*, 3016–3027. [CrossRef]
112. Lema, M.A.; Antonakoglou, K.; Sardis, F.; Sornkarn, N.; Condoluci, M.; Mahmoodi, T.; Dohler, M. 5G Case Study of Internet of Skills: Slicing the Human Senses. In Proceedings of the 2017 European Conference on Networks and Communications (EuCNC), Oulu, Finland, 12–15 June 2017; pp. 1–6.
113. Miao, Y.; Jiang, Y.; Peng, L.; Hossain, M.S.; Muhammad, G. Telesurgery Robot Based on 5G Tactile Internet. *Mob. Netw. Appl.* **2018**, *23*, 1645–1654. [CrossRef]
114. Meryem, S.; Adnan, A.; Mischa, D. The 5G-Enabled Tactile Internet: Applications, Requirements, and Architecture. In Proceedings of the IEEE Wireless Communications and Networking Conference (WCNC), Doha, Qatar, 3–6 April 2016; pp. 1–6.
115. Katz, M.; Pirinen, P.; Posti, H. Towards 6G: Getting Ready for the next Decade. In Proceedings of the 2019 16th international symposium on wireless communication systems (ISWCS), Oulu, Finland, 27–30 August 2019; pp. 714–718.
116. Bermejo, C.; Hui, P. A Survey on Haptic Technologies for Mobile Augmented Reality. *arXiv* **2017**, arXiv:1709.00698. [CrossRef]
117. Condoluci, M.; Mahmoodi, T.; Steinbach, E.; Dohler, M. Soft Resource Reservation for Low-Delayed Teleoperation over Mobile Networks. *IEEE Access* **2017**, *5*, 10445–10455. [CrossRef]
118. Xu, X.; Liu, Q.; Steinbach, E. Toward QoE-Driven Dynamic Control Scheme Switching for Time-Delayed Teleoperation Systems: A Dedicated Case Study. In Proceedings of the 2017 IEEE International Symposium on Haptic, Audio and Visual Environments and Games (HAVE), Abu Dhabi, United Arab Emirates, 22–23 October 2017; pp. 1–6.
119. Dressler, F.; Klingler, F.; Segata, M.; Cigno, R.L. Cooperative Driving and the Tactile Internet. *Proc. IEEE* **2018**, *107*, 436–446. [CrossRef]
120. Tanwar, S.; Tyagi, S.; Budhiraja, I.; Kumar, N. Tactile Internet for Autonomous Vehicles: Latency and Reliability Analysis. *IEEE Wirel. Commun.* **2019**, *26*, 66–72. [CrossRef]
121. Anthes, C.; García-Hernández, R.J.; Wiedemann, M.; Kranzlmüller, D. State of the Art of Virtual Reality Technology. In Proceedings of the 2016 IEEE Aerospace Conference, Big Sky, MT, USA, 5–12 March 2016; pp. 1–19.
122. Devagiri, J.S.; Paheding, S.; Niyaz, Q.; Yang, X.; Smith, S. Augmented Reality and Artificial Intelligence in Industry: Trends, Tools, and Future Challenges. *Expert Syst. Appl.* **2022**, *207*, 118002. [CrossRef]
123. Kosa, M.; Uysal, A.; Eren, P.E. Acceptance of Virtual Reality Games: A Multi-Theory Approach. In *Research Anthology on Game Design, Development, Usage, and Social Impact*; IGI Global: Hershey, PA, USA, 2023; pp. 31–61.
124. Popović, N. Tactile Internet in Future Industrial Automation Applications. In Proceedings of the 2022 21st International Symposium INFOTEH-JAHORINA (INFOTEH), East Sarajevo, Bosnia and Herzegovina, 16–18 March 2022; pp. 1–6.
125. Coutinho, R.W.; Boukerche, A. Design of Edge Computing for 5G-Enabled Tactile Internet-Based Industrial Applications. *IEEE Commun. Mag.* **2022**, *60*, 60–66. [CrossRef]
126. Wu, Y.; Yue, C.; Yang, Y.; Ao, L. Resource Allocation for D2D-Assisted Haptic Communications. *Digit. Commun. Netw.* **2022**, *in press*. [CrossRef]
127. ArunKumar, S.; Sivakami, K.; VijayaKarthik, S.V.; Deepa, S.M. 6G with Smart Healthcare, Haptic Communication. In *Handbook of Research on Design, Deployment, Automation, and Testing Strategies for 6G Mobile Core Network*; IGI Global: Hershey, PA, USA, 2022; pp. 303–329.
128. Dixit, S.; Bhatia, V.; Khanganba, S.P.; Agrawal, A. Future Challenges. In *6G: Sustainable Development for Rural and Remote Communities*; Springer: Berlin/Heidelberg, Germany, 2022; pp. 81–104.
129. Ikram, M.; Sultan, K.; Lateef, M.F.; Alqadami, A.S. A Road towards 6G Communication—A Review of 5G Antennas, Arrays, and Wearable Devices. *Electronics* **2022**, *11*, 169. [CrossRef]
130. Azari, M.M.; Solanki, S.; Chatzinotas, S.; Kodheli, O.; Sallouha, H.; Colpaert, A.; Montoya, J.F.M.; Pollin, S.; Haqiqatnejad, A.; Mostaani, A. Evolution of Non-Terrestrial Networks from 5G to 6G: A Survey. *IEEE Commun. Surv. Tutor.* **2022**, *24*, 2633–2672. [CrossRef]
131. Jun, S.; Kang, Y.; Kim, J.; Kim, C. Ultra-Low-Latency Services in 5G Systems: A Perspective from 3GPP Standards. *ETRI J.* **2020**, *42*, 721–733. [CrossRef]
132. Ghosh, A.; Maeder, A.; Baker, M.; Chandramouli, D. 5G Evolution: A View on 5G Cellular Technology beyond 3GPP Release 15. *IEEE Access* **2019**, *7*, 127639–127651. [CrossRef]
133. Peisa, J.; Persson, P.; Parkvall, S.; Dahlman, E.; Grøvlen, A.; Hoymann, C.; Gerstenberger, D. 5G Evolution: 3GPP Releases 16 & 17 Overview. *Ericsson Technol. Rev.* **2020**, *2020*, 2–13.
134. Baek, S.; Kim, D.; Tesanovic, M.; Agiwal, A. 3GPP New Radio Release 16: Evolution of 5G for Industrial Internet of Things. *IEEE Commun. Mag.* **2021**, *59*, 41–47. [CrossRef]
135. Le, T.-K.; Salim, U.; Kaltenberger, F. An Overview of Physical Layer Design for Ultra-Reliable Low-Latency Communications in 3GPP Releases 15, 16, and 17. *IEEE Access* **2020**, *9*, 433–444. [CrossRef]

136. Sharma, S.K.; Wang, X. Toward Massive Machine Type Communications in Ultra-Dense Cellular IoT Networks: Current Issues and Machine Learning-Assisted Solutions. *IEEE Commun. Surv. Tutor.* **2019**, *22*, 426–471. [CrossRef]
137. Mahmood, N.H.; Alves, H.; López, O.A.; Shehab, M.; Osorio, D.P.M.; Latva-Aho, M. Six Key Features of Machine Type Communication in 6G. In Proceedings of the 2020 2nd 6G Wireless Summit (6G SUMMIT), Levi, Finland, 17–20 March 2020; pp. 1–5.
138. Abdelsadek, M.Y.M. Optimized Resource Allocation Techniques for Critical Machine-Type Communications in Mixed LTE Networks. Ph.D. Thesis, Memorial University of Newfoundland, Norris Point, NL, Canada, 2020.
139. Mirkovic, D.; Armitage, G.; Branch, P. A Survey of Round Trip Time Prediction Systems. *IEEE Commun. Surv. Tutor.* **2018**, *20*, 1758–1776. [CrossRef]
140. Lema, M.A.; Laya, A.; Mahmoodi, T.; Cuevas, M.; Sachs, J.; Markendahl, J.; Dohler, M. Business Case and Technology Analysis for 5G Low Latency Applications. *IEEE Access* **2017**, *5*, 5917–5935. [CrossRef]
141. Huang, J.; Qian, F.; Gerber, A.; Mao, Z.M.; Sen, S.; Spatscheck, O. A Close Examination of Performance and Power Characteristics of 4G LTE Networks. In Proceedings of the 10th International Conference on Mobile Systems, Applications, and Services, Windermere, UK, 25–29 June 2012; pp. 225–238.
142. Hou, Z.; She, C.; Li, Y.; Niyato, D.; Dohler, M.; Vucetic, B. Intelligent Communications for Tactile Internet in 6G: Requirements, Technologies, and Challenges. *IEEE Commun. Mag.* **2021**, *59*, 82–88. [CrossRef]
143. Shahraki, A.; Abbasi, M.; Piran, M.; Taherkordi, A. A Comprehensive Survey on 6G Networks: Applications, Core Services, Enabling Technologies, and Future Challenges. *arXiv* **2021**, arXiv:2101.12475.
144. Lu, Y.; Zheng, X. 6G: A Survey on Technologies, Scenarios, Challenges, and the Related Issues. *J. Ind. Inf. Integr.* **2020**, *19*, 100158. [CrossRef]
145. Gustavsson, U.; Frenger, P.; Fager, C.; Eriksson, T.; Zirath, H.; Dielacher, F.; Studer, C.; Pärssinen, A.; Correia, R.; Matos, J.N. Implementation Challenges and Opportunities in Beyond-5G and 6G Communication. *IEEE J. Microw.* **2021**, *1*, 86–100. [CrossRef]
146. Geraci, G.; Garcia-Rodriguez, A.; Azari, M.M.; Lozano, A.; Mezzavilla, M.; Chatzinotas, S.; Chen, Y.; Rangan, S.; Di Renzo, M. What Will the Future of UAV Cellular Communications Be? A Flight from 5G to 6G. *IEEE Commun. Surv. Tutor.* **2022**, *24*, 1304–1335. [CrossRef]
147. Clazzer, F.; Munari, A.; Liva, G.; Lazaro, F.; Stefanovic, C.; Popovski, P. From 5G to 6G: Has the Time for Modern Random Access Come? *arXiv* **2019**, arXiv:1903.03063.
148. Petrov, I.; Janevski, T. Advanced 5G-TCP: Transport Protocol for 5G Mobile Networks. In Proceedings of the 2017 14th IEEE Annual Consumer Communications & Networking Conference (CCNC), Las Vegas, NV, USA, 8–11 January 2017; pp. 103–107.
149. Ezenwigbo, A.; Paranthaman, V.V.; Trestian, R.; Mapp, G.; Sardis, F. Exploring a New Transport Protocol for Vehicular Networks. In Proceedings of the 2018 Fifth International Conference on Internet of Things: Systems, Management and Security, Valencia, Spain, 15–18 October 2018; pp. 287–294.
150. Budhiraja, I.; Tyagi, S.; Tanwar, S.; Kumar, N.; Rodrigues, J.J. Tactile Internet for Smart Communities in 5G: An Insight for NOMA-Based Solutions. *IEEE Trans. Ind. Inform.* **2019**, *15*, 3104–3112. [CrossRef]
151. Achilli, G.M.; Logozzo, S.; Valigi, M.C. An Educational Test Rig for Kinesthetic Learning of Mechanisms for Underactuated Robotic Hands. *Robotics* **2022**, *11*, 115. [CrossRef]
152. Hamza-Lup, F. Kinesthetic Learning–Haptic User Interfaces for Gyroscopic Precession Simulation. *arXiv* **2019**, arXiv:1908.09082.
153. Zeng, C.; Zhao, T.; Liu, Q.; Xu, Y.; Wang, K. Perception-Lossless Codec of Haptic Data with Low Delay. In Proceedings of the Proceedings of the 28th ACM International Conference on Multimedia, Seattle, WA, USA, 12–16 October 2020; pp. 3642–3650.
154. Tan, H.Z.; Choi, S.; Lau, F.W.; Abnousi, F. Methodology for Maximizing Information Transmission of Haptic Devices: A Survey. *Proc. IEEE* **2020**, *108*, 945–965. [CrossRef]
155. Dangxiao, W.; Yuan, G.U.O.; Shiyi, L.I.U.; Zhang, Y.; Weiliang, X.; Jing, X. Haptic Display for Virtual Reality: Progress and Challenges. *Virtual Real. Intell. Hardw.* **2019**, *1*, 136–162.
156. Wee, C.; Yap, K.M.; Lim, W.N. Haptic Interfaces for Virtual Reality: Challenges and Research Directions. *IEEE Access* **2021**, *9*, 112145–112162. [CrossRef]
157. Yin, J.; Hinchet, R.; Shea, H.; Majidi, C. Wearable Soft Technologies for Haptic Sensing and Feedback. *Adv. Funct. Mater.* **2021**, *31*, 2007428. [CrossRef]
158. Bai, H.; Li, S.; Shepherd, R.F. Elastomeric Haptic Devices for Virtual and Augmented Reality. *Adv. Funct. Mater.* **2021**, *31*, 2009364. [CrossRef]
159. Choi, D.-S.; Lee, S.-H.; Kim, S.-Y. Transparent and Soft Haptic Actuator for Interaction with Flexible/Deformable Devices. *IEEE Access* **2020**, *8*, 170853–170861. [CrossRef]
160. Cheok, A.D. An Instrument for Remote Kissing and Engineering Measurement of Its Communication Effects Including Modified Turing Test. *IEEE Open J. Comput. Soc.* **2020**, *1*, 107–120. [CrossRef]
161. Wei, X.; Duan, Q.; Zhou, L. A QoE-Driven Tactile Internet Architecture for Smart City. *IEEE Netw.* **2019**, *34*, 130–136. [CrossRef]
162. Sharma, S.K.; Woungang, I.; Anpalagan, A.; Chatzinotas, S. Toward Tactile Internet in beyond 5G Era: Recent Advances, Current Issues, and Future Directions. *IEEE Access* **2020**, *8*, 56948–56991. [CrossRef]
163. Steinbach, E.; Strese, M.; Eid, M.; Liu, X.; Bhardwaj, A.; Liu, Q.; Al-Ja'afreh, M.; Mahmoodi, T.; Hassen, R.; El Saddik, A. Haptic Codecs for the Tactile Internet. *Proc. IEEE* **2018**, *107*, 447–470. [CrossRef]

164. Wei, X.; Shi, Y.; Zhou, L. Haptic Signal Reconstruction for Cross-Modal Communications. *IEEE Trans. Multimed.* **2021**, *24*, 4514–4525. [CrossRef]
165. Eid, M.; Cha, J.; El Saddik, A. Admux: An Adaptive Multiplexer for Haptic–Audio–Visual Data Communication. *IEEE Trans. Instrum. Meas.* **2010**, *60*, 21–31. [CrossRef]

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