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Review

A Survey of the Tactile Internet: Design Issues and Challenges, Applications, and Future Directions

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Abstract: The Tactile Internet (TI) is an emerging area of research involving 5G and beyond (B5G) communications to enable real-time interaction of haptic data over the Internet between tactile ends, with audio-visual data as feedback. This emerging TI technology is viewed as the next evolutionary step for the Internet of Things (IoT) and is expected to bring about a massive change in Healthcare 4.0, Industry 4.0 and autonomous vehicles to resolve complicated issues in modern society. This vision of TI makes a dream into a reality. This article aims to provide a comprehensive survey of TI, focussing on design architecture, key application areas, potential enabling technologies, current issues, and challenges to realise it. To illustrate the novelty of our work, we present a brainstorming mind-map of all the topics discussed in this article. We emphasise the design aspects of the TI and discuss the three main sections of the TI, i.e., master, network, and slave sections, with a focus on the proposed application-centric design architecture. With the help of the proposed illustrative diagrams of use cases, we discuss and tabulate the possible applications of the TI with a 5G framework and its requirements. Then, we extensively address the currently identified issues and challenges with promising potential enablers of the TI. Moreover, a comprehensive review focussing on related articles on enabling technologies is explored, including Fifth Generation (5G), Software-Defined Networking (SDN), Network Function Virtualisation (NFV), Cloud/Edge/Fog Computing, Multiple Access, and Network Coding. Finally, we conclude the survey with several research issues that are open for further investigation. Thus, the survey provides insights into the TI that can help network researchers and engineers to contribute further towards developing the next-generation Internet.

Keywords: tactile internet; beyond 5G; software-defined network; network function virtualisation; multiple-access techniques; 1 ms challenge; round-trip time

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1. Introduction

The Tactile Internet (TI) is an innovation that facilitates interaction between human beings (possibly over a distance) with visual presence and haptic feedback [1]. In June 2015, the Technical Activities Board Future Directions Committee launched the most current activity for the Institute of Electrical and Electronics Engineers (IEEE) Digital Senses Initiative (DSI). The DSI is devoted to propelling advancements that catch and recreate human activities such as sense, touch, hearing, taste, and sight from the external world. These human activities are received and reacted to by machines and humans in different manners.

In a meeting held in 2013, a future financial "golden age" of technological association was considered during the 2020s, where a significant amount of regular day-to-day work might be progressively carried out by robots [2]. For example, the alluring chance of monitoring is imagined by sitting in one site and reacting remotely through the Internet at another site far from the original one. However, the conception of the Internet as the Tactile Internet (TI) was broadly announced by Fettweis in mid-2014 [3,4], where he mentioned that the TI has the potential for a plethora of use cases that influence our lives and the world economy.

One of the requirements of real-time Cyber-Physical Systems (CPSs) is to have a round-trip time (RTT) of below 1 ms. A significant example is the CPS model for the smart grid, and the requirement of rapid reaction time in situations with power-network failures. Recent cellular and wireless local area networks (WLANs) fail to achieve this objective by a considerable order of magnitude. By achieving an RTT of 1 ms, the user can explore the new era of the TI by changing the experience of current mobile broadband applications. Along with voice and data communications, current fourth-generation (4G) systems empower continuous access to massive data for applications, such as machine-to-machine (M2M) or machine-type communication (MTC). The next major step is to associate multiple machines together, and control them from a far distance. Therefore, for control communication, this will create another approach to guide and control factors of our environment and its conditions [3]. With the help of carrier-grade robustness and accessibility, the demand for a RTT of 1 ms will empower the TI for guiding and controlling real and virtual objects [4].

However, the TI comes with a warning that it should be able to tell the difference between humans and machines. This should be applicable where there is a large requirement of machines and less interference from humans. Machines should complement humans, instead of acting as a substitute for them [5].

Ultimately, features such as delivering up to 1000 times more capacity, maximum data rates at 10 Gbps, and interconnections of at least 100 billion end-user devices are expected to be realised for the 5G communication system, compared with 4G. The primary purpose of 5G systems is to construct and handle novel machine-driven applications that are not tended to by cellular networks. Compared to the past four generations, the vision of 5G will be considerably flexible to integrate with cellular and wireless-fidelity (Wi-Fi) technologies and their standards. Furthermore, the crucial part of the envisioned 5G communication systems is transforming the distributed core infrastructure into a device-based infrastructure and employing Artificial Intelligence (AI) at the end-user device location or on user equipment (UE) with assisted mobility and device-to-device (D2D) communication.

1.1. Vision of the Tactile Internet

For a wide range of application areas such as Industry 4.0, smart e-learning and education, and Healthcare 4.0, the Tactile Internet (TI) envisions the interaction of human-to-machine (H2M) and relies upon it to add another paradigm to see its influence on society. The envisioned TI desires to meet the stringent design requirements by empowering a suitable communication framework. First, it needs to give an extremely low round-trip time (delay) of 1 ms or below, and possible ultra-high reliability to avoid motion sickness. It likewise needs to guarantee data security and high availability of a framework without compromising the ultra-low latency requirement. These crucial design goals of TI can be achieved by placing tactile devices close to each other, which is often based on distributed or decentralised architecture dependent on recent technological advancements such as Edge/Fog Computing, Software-Defined Networking (SDN), and Network Coding, Network Function Virtualisation (NFV), and suitable multiple-access (MA) techniques. Moreover, adaptable techniques at all protocol layers are expected to minimise the RTT from sensors to actuators.

Significantly, the TI will establish vital prerequisites for next-generation access networks as far as latency, availability, and reliability are concerned. Wired access networks are ultimately fulfilling these prerequisites already, and wireless access networks are not yet proposed to fulfil these prerequisites. As per the International Telecommunication Union—Telecommunication Standardisation Sector (ITU-T) Technology Watch Report on the TI [1], research in these areas will need to speed up substantially, introducing new thoughts and designs to promote access network characteristic redundancy, and a decent variety to resolve RTT issues and reliability constraints of TI applications.

As TI is going to serve critical applications of society, it should have competencies such as ultra-reliability [6], very low latencies, and be able to connect to numerous devices for communicating with each other simultaneously and autonomously. It should also be feasible to interact with ongoing and conventional wired Internet, mobile Internet and the IoT, thus forming a network of entirely new possibilities and opportunities.

1.2. Evolution of the TI

With regard to TI, Figure 1 depicts the progressive evolution of TI, as indicated by an ongoing ITU-T Technology Watch Report [1]. According to the definition given by the ITU-T Technology Watch Report, the Internet that comprises ultra-low latency, ultra-high availability, ultra-high reliability, ultra-responsive, fast reaction times, scalability and security, is referred to as TI. On the other hand, the interconnection of physical devices with the Internet with requirements such as power efficiency, surveillance and data security, reliability, good energy management, relatively low throughput and effective low latency, is referred to as the Internet of Things (IoT). In contrast, the Internet with transmission of voice and data, video-streaming content, web browsing and telephony, is referred to as mobile Internet.

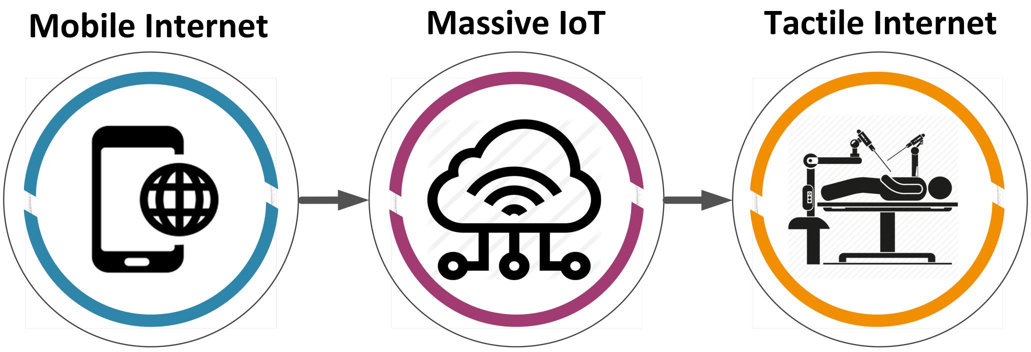

Figure 1. The evolution of TI.

Mobile communication contributes is crucial to the modern telecommunication infrastructure. In the 1990s, various versatile computers such as laptops, pagers, cell phones and personal digital assistant (PDA) phones were announced. Generations of mobile communication, i.e., 2G, 3G, 4G and 5G and their wireless communication services such as Universal Mobile Telecommunications Service (UMTS), General Packet Radio Services (GPRS), and Enhanced Data Rates for GSM (Global System For Mobile) Evolution (EDGE), have profited businesses as well as delivered comfort to the end user. These services have effectively linked tons of end users to physical devices. The 5G framework permits human-to-human (H2H) communication to trade multimedia content such as audio and video information. The primary centre of attention for the mobile Internet is facilitating the integration between end-user devices and the machines, thus implied as the IoT.

After the evolution of the mobile Internet, the IoT is a concept that involves the communication of two or more devices that integrate the Internet and the cloud. Applications related to IoT have been investigated more as it offers considerable chances to ease life. They depend on H2M and D2D communication [7]. However, the IoT has a few demerits, such as low data rate, decent latency, surveillance and security, low compatibility, and privacy. Hence, the shortcomings of the IoT could be overcome by the "Tactile Internet" (TI), which is the progressive evolution of the IoT that manages networks in a real-time environment.

The TI currently exists at the conceptual stage, and a lot of research is still needed to revolutionise it. The idea of the TI is becoming broader, where a human can interact with another human, which grants us an option to transmit a sense of touch and actuation over a long distance in real time with or without audio/visual feedback. These requirements in TI permit tactile end devices to sense and actuate in real-time transmissions over distance/remote communications. It will reform all aspects of society, culture and use cases such as eHealthcare, industry, and much more.

Thus, information-delivery networks can be fundamentally transformed into skillset-delivery networks. Low-power massive connections, ultra-responsive, ultra-reliable and ultra-fast reaction times of the TI will enumerate another H2M interconnection paradigm by empowering haptic features. Conversely, 5G and beyond should be able to manage the extraordinary increment of mobile data traffic and the immense proportion of information from intelligent devices that will energise IoT applications. Each evolution step states some features that are required for an accessible mode of communication.

1.3. Recent Advances in the Tactile Internet

Recently, because of the emergence of the Tactile Internet (TI), a remarkable amount of research has been substantially carried out. These studies are generally inspired by several applications such as self-driving vehicles, augmented reality (AR), virtual reality (VR), Industry 4.0, Healthcare 4.0, immersive virtual reality (IVR), teleoperation systems, telementoring, remote driving, and tactile robots. The existing system models and architectures are still theoretically and technically inadequate to realise the arising TI applications. Due to the non-traditional requirements and demands for TI in future B5G networks, factors such as Fog/Edge clouds, sensors and actuators at the master and slave sides, RTT, reliability, system models, and architecture are taken into consideration.

In addition, the speed of light is 3×10^8 m/s, i.e., light travels 300 km in 1 ms. To meet the requirements of the TI RTT, the control server and tactile ends can be at a maximum of 150 km. Thus, the limiting parameter, i.e., the speed of light, also affects the speed of human interaction with humans/machines.

Furthermore, considering the stringent demands and requirements of TI involving ultra-low latency and ultra-high reliability, features such as data integrity, security, encryption, and network availability need to be established with fewer trade-offs between these. However, the existing centralised infrastructure is not adequate to meet these features. Therefore, more distributed infrastructure based on Fog/Edge computing should be adequately examined to bring TI applications nearer to end users [8].

Additionally, it is crucial to refresh next-generation wireless access networks by exploring novel resource allocation in network slicing, feedback mechanisms of the sensors/actuators, interference management and multiple-access techniques to satisfy the potential demands and requirements of TI applications [1].

Moreover, considerable research has been carried out on haptic devices such as tactile gloves, etc., and kinematic devices such as capacitive-based, magnetic-based, piezoelectric and image sensors, and tactile support engines with AI compatibility for information integration and decision boxes [9].

The demand for interdisciplinary research is crucial in planning and designing intelligent tactile sensors considering fabrication techniques/technologies, the material of sensors/devices, intelligent signal processing and machine-learning algorithms to analyse the behaviour of the sensing device and process complex data coming to the sensors. Several factors are necessary to realise the TI, such as security, reliability, availability, and latency in wireless transmission of tactile sensing data, thus giving the experience of remote real touch feeling and control. A few standardised works are forecasted to collaborate between the TI's use cases and the improvement of current wireless sensor networks.

Considering ongoing standardisation, a new IEEE standard family has been defined for the TI, i.e., IEEE P1918.X [10,11]. IEEE P1918.X describes the architecture technology and assumptions in the TI, whereas IEEE P1918.X.1, IEEE P1918.X.2 and IEEE P1918.X.3 are focussed on codecs, AI and towards MAC for the TI, respectively. In addition, a considerable amount of work has been done to develop a working group for low-latency Industrial IoT (IIoT) such as intelligent transportation systems, Industry 4.0, and Health 4.0 [12].

1.4. Research Motivation

One of the reasons to carry out the research is the TI's emerging research area, where there is a need to improve the round-trip time (RTT) and reliability in the system. This improvement will ensure and enable the smooth functioning of the system without cyber or motion sickness (lag). The crucial challenge to achieve tolerable RTT of 1 ms is essential to facilitate the services and applications related to the TI. Still, there are many challenging solutions to reduce the RTT over the network. Therefore, we have been motivated to adopt TI technology to incorporate technological advancements such as SDN, NFV, Network Coding, physical MAC-layer protocols and cloud networking technologies, which promise to serve the requirements of the TI.

1.5. Main Contribution

Although quite a few survey papers have talked about the overview of the TI, they are not mainly focussed on the design architecture, applications, and current issues. Thus, they do not provide illustrative diagrams for the reader to comprehend the gist of the research altogether. Here, we briefly highlight the main contributions of this survey as follows.

- We emphasise the TI design aspects with proposed application-centric design architecture, where the main sections of the architecture, i.e., master, network, and slave sections, with their functions, are explored.
- We identify the key application areas and provide discussions with proposed illustrative diagrams of use cases. Moreover, the multiple application scenarios with required the TI competencies and their performance metrics are tabulated.
- We provide an in-depth discussion of the identified current issues and challenges with potential enablers of the TI. In addition, some possible future research directions are provided to give an insight to researchers.
- We present a comprehensive review focussing on the related articles on enabling technologies such as 5G, SDN, NFV, Cloud/Edge/Fog Computing, Multiple Access, and Network Coding to realise the TI. Here, the contribution of the related articles is summarised according to enabling technologies.

1.6. Structure of the Article

A list of abbreviations and their definitions is shown in Appendix A. Figure 2 shows a graphical overview of all the topics covered for design, applications, and challenges related to the TI in the form of a mind-map. The remainder of this paper is structured as follows. The design aspects of the TI are discussed in Section 2. The applications of the TI are elaborated in Section 3. The current issues and challenges in realising the TI are discussed in Section 4. Section 5 provides a thorough review of related articles, and a summary of research challenges is presented in Section 6. Finally, Section 7 concludes the paper along with future research directions.

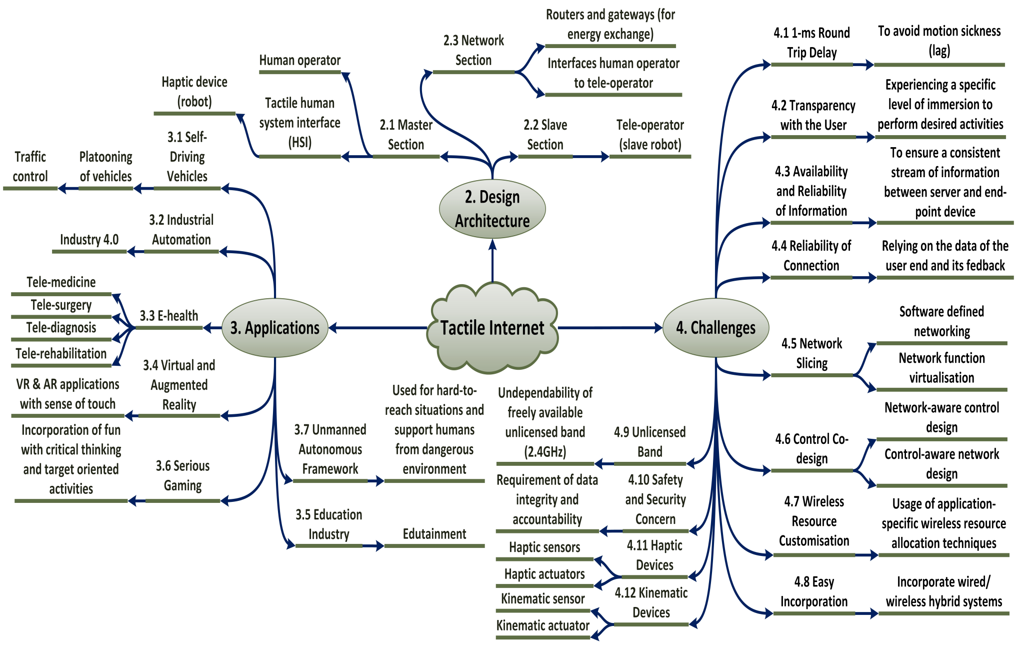

Figure 2. A mind-map of the topics related to the Tactile Internet (TI) discussed in this research.

2. Design Aspects of the Tactile Internet

The Tactile Internet (TI) has some features that are not apparent on the traditional Internet. The traditional Internet facilitates audio and visual communication, whereas the TI facilitates transmitting a sense of touch and actuation along with haptic feedback.

The TI depends on haptic and non-haptic control to have communication between end-to-end operations. Figure 3 is the pictorial representation of the architectural design of the TI, which consists of three sections, i.e., master, network, and slave sections. With haptic command and haptic feedback signals, the master and slave sections communicate via the network section. There is a two-way exchange of information between the master and slave sections.

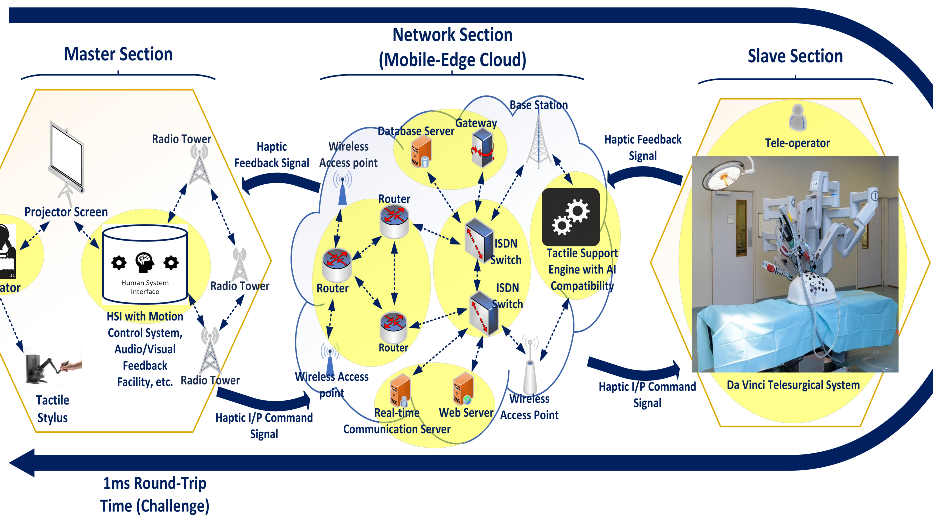

Figure 3. The design architecture for the end-to-end da Vinci telesurgical system.

2.1. Master Section

The master section is located at the front end of the TI system. It comprises a human operator with a tactile human–system interface (HSI). The input given by a human is then converted into tactile input by HSI. HSI is a master machine or robot which acts as a haptic device. A user is permitted to touch, feel, and manipulate in the real world.

Through the command signals, the operation of the slave is controlled by the master section. It ought to be noticed that numerous operators can cooperatively curb the activities of the slave section in most of the applications. The audio and visual feedback features are essential for haptic and non-haptic control of the slave section. Thus, it is crucial to increase perceptual performance as the human brain coordinates typically diverse with tangible approaches [13].

There are some haptic devices on the market which are accessible from merchants such as Sensable [14] and Geomagic [15]. These are meant for structuring a linkage-based framework, which comprises a robotic arm linked to a stylus. The robotic arm follows the movement of the stylus and is fit for applying force on its tip. To genuinely understand the vision of the TI, further advancements on haptic devices are required, especially in expanding the Degree of Freedom (DoF) to fulfil the needs of future applications. These haptic devices need to be interfaced with the network to have communication with the core network.

2.2. Slave Section

The slave section comprises a teleoperator (slave robot) and is legitimately constrained by the master section through numerous coding techniques and haptic input command (instruction) signals. The teleoperator performs multiple actions as instructed by the master section in the remote environment. In addition, the slave section does not have previous information about the surroundings. Subsequently, a global control loop is formed when communication is initiated between the master and slave sections through feedback and command signals. Here, the Da Vinci telesurgical system [16] example involves robotic arms being manipulated by a surgeon sitting at one console (master section) with video monitoring and joystick controller, which is approved by the United States Food and Drug Administration (FDA).

2.3. Network Section

This section is typically situated in the middle of the master and slave sections, and acts as a medium for two-way communication, thus interfaces the operator to the teleoperator (remote) environment.

It comprises routers and gateways, which facilitates a medium for two-way communication. The haptic input command signals are sent from the master section. Thus, the input signals pass through routers, switches, gateways, base stations, access points, database server and tactile support engine equipped with AI and reach slave section.

Thus, the global control loop is formed with the master and slave section, as the information is shared and exchanged between them with the help of command and feedback signals. AI is also facilitated by a tactile support engine and plays an essential job in processing latency-critical applications.

For real-time haptic communication, the network should have ultra-reliable and ultra-responsive connectivity, which reduces RTTs. To understand the requirement and vision of the TI, the foundation of 5G connectivity is required in the architecture of the TI system, which is composed of eNBs nodes (radio access network) and a core network.

Even though many kinds of research have been carried out on the 5G framework, there is no consistent concurrence on its architectural design. However, the consensus implies that the 5G framework must be planned in an adaptable environment. The end goal of having one network based on typical physical infrastructure is productively shared among various vertical applications. Here, the concept of NFV is taken into consideration, where the network is sliced according to the particular application's requirements.

Subsequently, interest in NFV [17] and SDN [18] has risen to shape an envisioned architectural design. NFV facilitates a detachment of network functions from the hardware system, and hence network slicing programming can be done and deployed in any standard distributed computing framework. On the contrary, SDN facilitates an architectural system, wherein the control plane and data plane are decoupled, thus empowering the network's software coding through its controllers.

3. Applications of the Tactile Internet

In various scenarios, communication will be enhanced through the Tactile Internet (TI), which will lead to increasingly reasonable social interaction. A portion of the imagined 5G-enabled tactile applications requires competencies such as RTT (1 ms or below), ultra-high availability and ultra-high reliability, whose reliability should be significant orders higher than in the current radio access network. It is also seen that existing wireless or cellular networks do not yield anything to accomplish an ultra-low latency of 1 ms and ultra-high reliability of 99.999%, which are essential for TI applications. In this way, it is troublesome to grasp all the possible emerging tactile applications at the early stage of 5G development. It could play a crucial role in eradicating the socio-economic boundaries of society [1]. Once the challenges are fulfilled, numerous applications can be explored and achieved with 5G mobile communications. Hence, the taxonomy of possible applications of TI with 5G framework and their requirements are presented in Table 1. However, TI can support various applications as some of the ideas are shared as follows.

Table 1. Possible applications of the TI with 5G framework and their requirements.

Application Area or Scenario	TI Competencies Needed	Performance Metrics with Requirements
• Self-driving Vehicles • Remote Driving • Industrial Automation • Virtual and Augmented Reality (AR and VR) • Unmanned Ariel Vehicle (UAVs) • Smart Grids • E-learning • Serious Gaming	• Ultra-high Reliability • Low Latency	• RTT (>1 ms) • Reliability (99.999%) • Date Rate (<250 Mbps)
• eHealth (Telesurgery) • Human-to-Machine Interaction • Immersive Virtual Reality (IVR) • Telementoring	• Ultra-low Latency	• RTT (≈2 ms)
• Cloud-based Telemedicine • Industry 4.0 or Industrial Internet	• Ultra-high Reliability • Ultra-high Availability	• RTT (<1 ms) • Reliability (≤99.999%) • Availability (≈100%)
• Artificial Satellite Communication for Emergency	• Ultra-high Availability	• Coverage and Excellent Service • Frequency (1 GHz to 50 GHz)

3.1. Self-Driving Vehicles

Self-driven vehicles are broadly classified to be designed and constructed along with the advancements of technological fields. Most of them can be partially driven or fully self-driven. The highlights of self-driven vehicles will deliver a new driving experience. By incorporating the unique features of autonomous vehicles, the consumer will take some time to have a hands-on and manage those features. The highlights of such vehicles can be electronic braking systems with emergency braking, automatic parking, and versatile cruise control, where a driver can put his/her vehicle on autopilot mode. Most of these highlighted features are present in selected applications of the controlled environment. The futuristic thought of a fully self-driven vehicle is no longer just a thought. Different organisations are already working on the driving features that enable a vehicle to drive itself.

The benefits of a self-driven vehicle are nominally reduced accident rates, self-parking, and less time consumption. Other highlights of the autonomous vehicle are having access to entertainment and digital media and more relaxation time, which will significantly impact the financial budget. Nonetheless, implementation of all the features of the autonomous vehicle comes at the expense of satisfying a few challenges, which further requires enormous improvements in (1) communication technology, (2) infrastructure for the sensor domain, and (3) communication between the vehicles to fetch significant information [19].

To encourage completely self-driving competencies, the development of the Intelligent Transport System (ITS) [20] has been enabled because of technological advancement in 5G wireless communication to connected and communicating vehicles. Hence, wireless communication technologies will significantly impact Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communication.

Considering enhanced security, there would be a manageable reduction of traffic jams and road accidents by adopting fully automated driving. In today's world, the time required to avoid any collision for the safety of the vehicle is 10 ms [21]. To serve the purpose of a bidirectional data exchange for automated vehicles, the RTT of communication should be in the order of milliseconds [22]. This can be acknowledged by the TI and its RTT (latency) of 1 ms. Figure 4 illustrates the platooning of self-driven vehicles by maintaining a fixed distance 'D' between them. All vehicles establish a connection to the nearest base station, thus reaching a fog network to execute the complex computation of the traffic.

3.2. Industrial Automation

For the TI, a steadily developing application field is in automation for industry. It not only boosts the overall production of infrastructure but also increases efficiency. One of the requirements of automation in industry is having RTT underneath 1 ms per sensor for industrial robots, where the sensitivity of control circuits matters the most when the controlling gadgets are moving quickly. To execute this entire base concept would require high-speed connectivity of millimetre-wave technology.

Due to the requirements of intelligent robots, smart devices, sensors, etc., globally, traditional industries are transforming into digital ones. There have been previously three generations in the industrial revolution, which resulted in profitable products in the industrial market [23].

A real-time empowered cyber-physical system creates a paradigm shift in the coming fourth industrial revolution (Industry 4.0). It comes with prime modifications in assembly, design, material usage and inventory networking, thus prompting adaptable and self-composed smart factories [24]. With increased features and adaptability, Industry 4.0 will empower individuals to individualise any item and transform according to market needs. Figure 5 illustrates an automated production assembly line where the machine and user communicate through a wireless access point. The user is equipped with a tablet that controls the machines present on the industry premises.

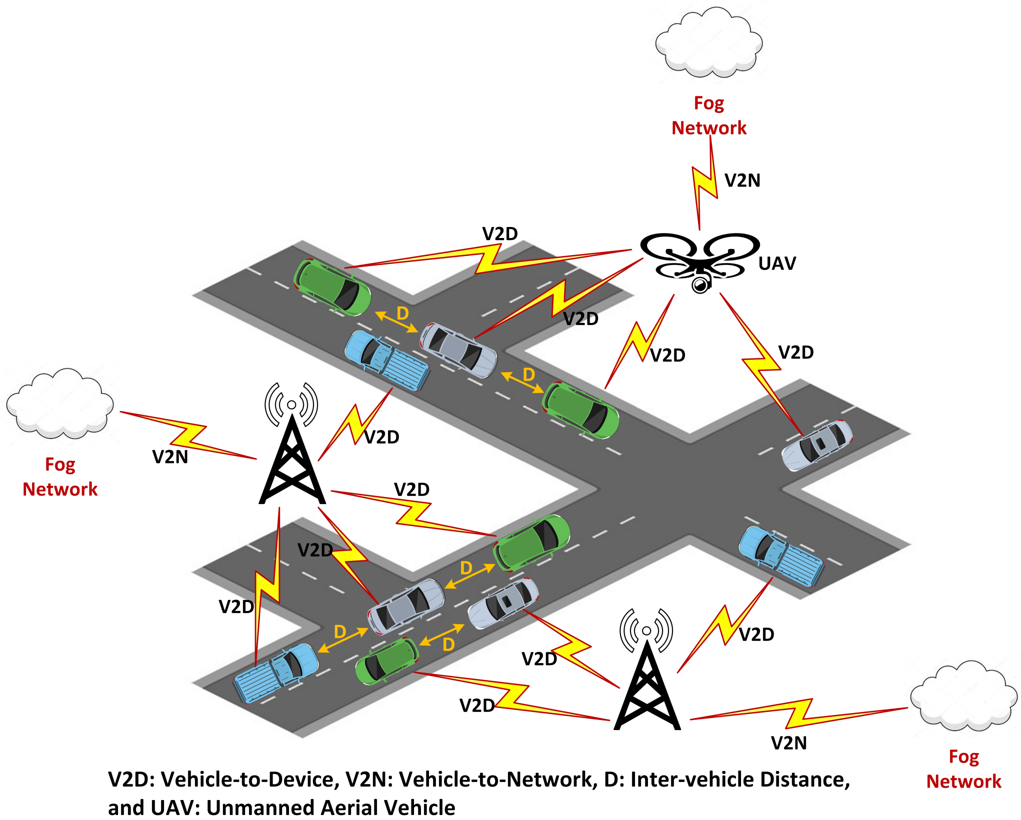

Figure 4. The platooning of self-driven vehicles maintaining a fixed distance 'D' between them.

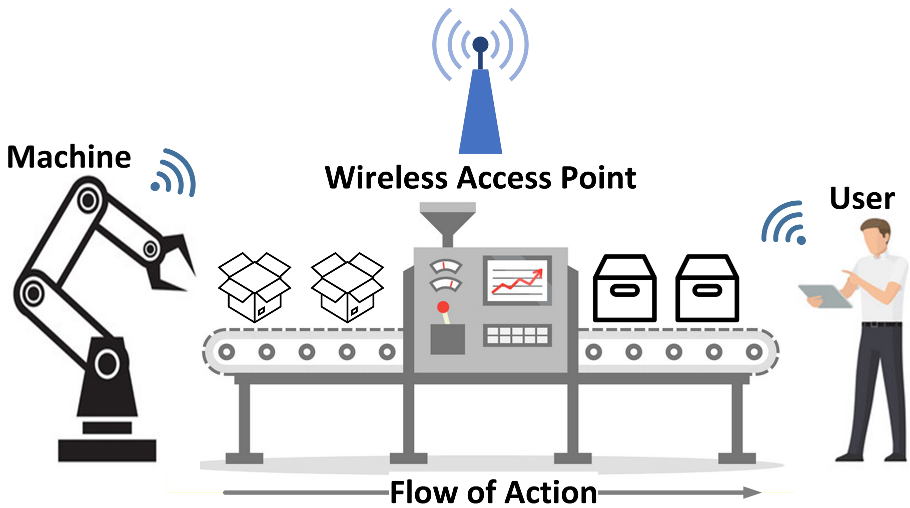

Figure 5. An automated production assembly line where the user is giving instructions wirelessly on a tablet in industry.

3.3. eHealth

eHealth is a significant concern for human health and safety. A large portion of the TI sector is networked wirelessly to propel and provide proper services to humans. An efficient way could be found where information-based healthcare services can make superior use of information to upgrade patient security. Furthermore, competencies such as efficiency, robustness and reliability of the healthcare system's services in teleservices (rehabilitation, surgery, and diagnosis), TI infrastructure and IEEE wireless standards need improvement [25]. It is observed that any delay in a non-real-time system can prompt a mistake in patient behaviour in the case of remotely assisted (robotic) telepresence surgery [26].

To overcome distant geographic places and increment access to medical services, telemedicine uses the TI infrastructure with wireless communication. A time could come when medical experts could be present (virtually) anywhere and without paying attention to doctors' location using advanced tele-diagnostic tools. Hence and so forth, without a doctor physically present at the patient's location, a telerobot can treat the patient operated by a doctor (remotely). Additionally, audio and visual information will be provided, along with haptic feedback. This will improve the possible future application of TI in health care which will incorporate telediagnosis, telesurgery and telerehabilitation.

It is fundamental to see that the capabilities of machines are growing. Therefore, the TI should give aid to humans rather than finding a replacement for them. This emergence of the TI should facilitate new options that enable humans by providing a hike in their career based on yields. Figure 6 illustrates robotic telesurgery with a master (operator) and slave (patient), which are physically present in remote locations. The operator's location will be equipped with a high-quality camera and controlling devices with haptic feedback. Therefore, the user (doctor) would feel being physically present in the patient's location.

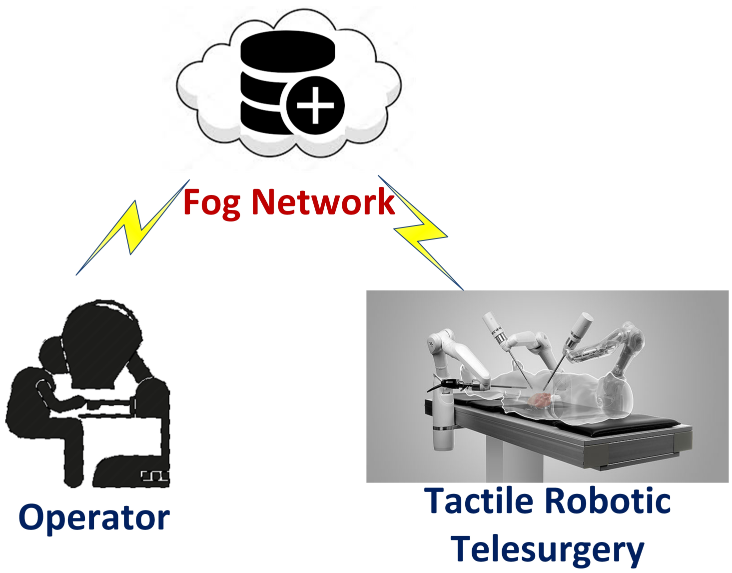

Figure 6. Robotic telesurgery with a master as 'operator' and slave as 'patient'.

3.4. Virtual and Augmented Reality

The availability of the TI can significantly aid by virtual reality (VR) and augmented reality (AR) applications. VR is a common, haptic virtual condition in which a few clients are physically coupled through software tools to mutually/cooperatively execute an operation by virtually seeing physical objects, not only by audio and video but also with a sense of touch.

The actual real view in this world is envisioned by incorporating computer-produced objects in AR. The significant objective of future AR applications is the representation of dynamic substance and up-to-date data. For high-dependency conversations happening between devices, haptic feedback in VR is essential. Exceptionally, depending on the sense of touch, many applications rely on object size and precision. This must be acknowledged if the RTT between users and VR is a couple of milliseconds.

There is a need to improve numerous assistance systems requiring the augmentation of extra information into the client's field of view, e.g., maintenance and education. The objects in AR can be dragged from static to dynamic with the help of the TI. This offers a clear picture of real-time objects such that dangerous events such as car accidents can be distinguished and avoided.

Based on the 5G user experience along with AR and VR, there are six types of expected experiences: behavioural, emotional, social, cognitive, sensory, and basic. Each experience impacts the constituent elements of AR and VR related to the TI. The constituent elements of AR and VR include Visual Enhancement (Input and Control), Context-aware (Initiative), Environment and Familiarity, Information Embedding, Content Creation, Interactivity, Geolocation, Portability and Wearability, and User and Technical Guidance. Table 2 will provide the constituent elements of the AR and VR experiences. Figure 7 shows that the user is experiencing the virtual reality of touching a wild animal with haptic feedback. The education industry will also benefit if VR-based study-related applications are incorporated into a learner's curriculum. The learner would feel the animals, which will create a high sense of immersive tactile learning.

Table 2. Mapping of types of AR and VR experience with the constituent components that influence the 5G User Experience (UX).

Types of Experience	Influential Constituent Elements of AR and VR	References
Behavioural Experience	Interactivity, Context-aware, Portability and Wearability, Information Embedding	
Emotional Experience	Visual Enhancement (Input), Information Embedding and Context-aware	
Social Experience	Context-aware, Information Embedding and Visual Enhancement (Input)	
Cognitive Experience	Information Embedding, Content Creation and Visual Enhancement (Input)	[27–31]
Sensory Experience	Portability and Wearability, Geolocation and Visual Enhancement (Input and control)	
Basic Experience	User and Technical Guidance, Context-aware, Information Embedding, Visual Enhancement and Interactivity	

3.5. Education

The TI will empower enhanced learning dependent on the haptic overlay of the educator and learner. By consolidating TI with VR and AR, comprehension-based learning will boost the learner's interests and surpass traditional learning methods. Subsequently, the learner will pursue an opportunity to adapt generally through exploring and discovering the content available. A plus point will be that there will be less interference from the educator and no educator pressure on the learner to study. With the incorporation of VR-based study-related applications in the learner's curriculum, the learner would be fully immersed in tactile learning by touching virtual things provided with haptic feedback, as illustrated in Figure 7.

3.6. Serious Gaming

Serious gaming is an activity intended for a reason other than entertainment. For example, these activities incorporate fun with critical thinking challenges and target-oriented activities. In other terms, serious games also influence various application fields imperative to the general public, including health, education, and training.

What restricts its advancement is the RTT of the communication frameworks, as the recognisable RTTs legitimately impact the apparent authenticity of applications. Thus, the task could be made conceivable, e.g., designing a game application for a learner to simulate the dental care of a patient. The intended purpose will be to promote knowledge about oral care to interact with haptic devices.

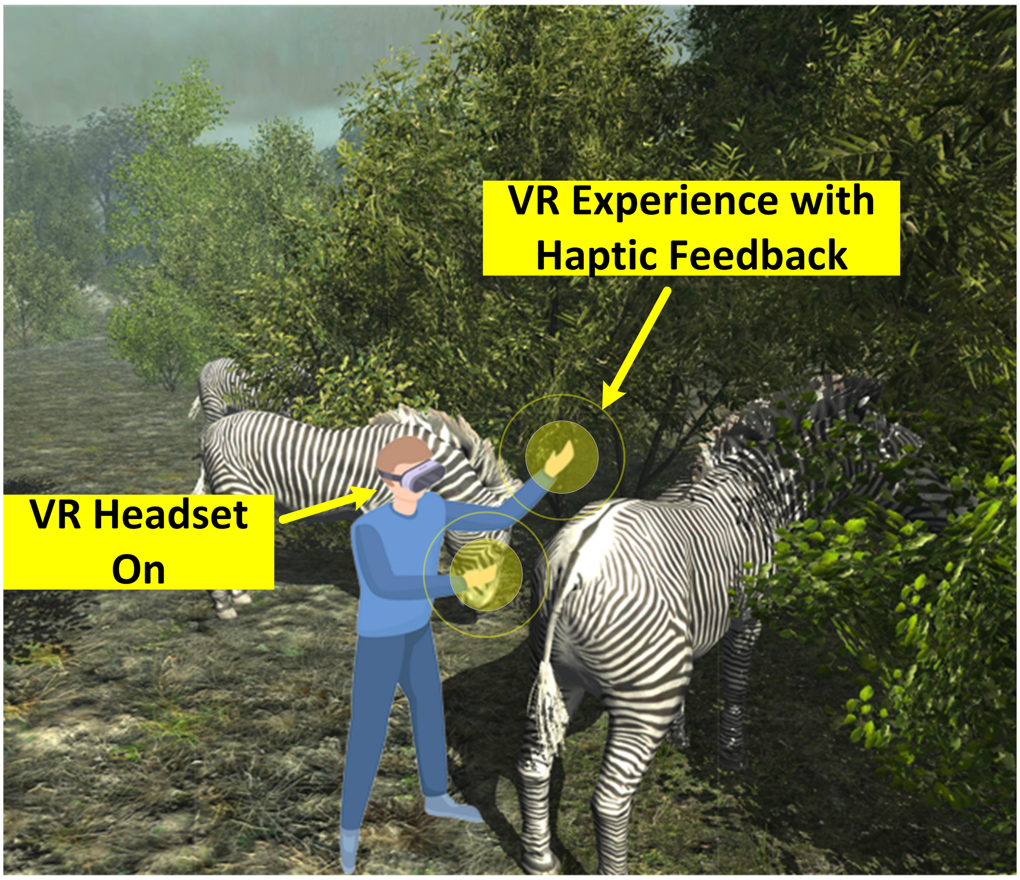

Figure 7. The user experiencing virtual reality of touching the wild animal.

3.7. Other TI Applications

Another TI application includes the unmanned autonomous framework. For instance, industrial manufacturing products lined up on assembly line-based production requires mobile robots to help and deliver the assembly parts on demand. This process requires a highly reliable tactile communication framework to carry out the operation. These frameworks are now extensively used in hard-to-reach situations and provide support to humans in a dangerous environment. For example, a drone with a high-precision remote control and without minimised RTT operated by a human can be significantly used as a TI application.

4. Current Issues and Challenges of Realising the Tactile Internet

The two most challenging objectives for accomplishing communication features are to achieve ultra-low latency (1 ms or below) and ultra-high reliability (99.999%, i.e., a one-in-one-million chance of failure). There are numerous challenges related to the requirements for Tactile Internet (TI) communication. These requirements focus on Quality of Experience (QoE) [32] to improve user experience. The following is a list of requirements needed for the TI. In addition, Table 3 provides a discussion on open challenges with descriptions and potential enablers/solutions.

Table 3. Open challenges with descriptions and potential enablers/solutions.

Challenges	Description	Potential Enabler and Solution with References
Ultra-low Latency (1 ms RTT)	To avoid noticeable motion sickness (lag).	• Emerging Passive Optical Local Area (POL) technology [33]. • Employing short frame transmission structure [34]. • Needing physical layer and control (MAC) layer techniques. • Relating to core network: SDN-based methods, NFV-based methods, Fog/Edge-based designs and Directory-based architectures [35–42].
Transparency with the User	Action performed in real time must be the same in the remote scenario to have desired feedback to the end user. Experience a specific level of immersion to perform desired activities.	• Faultless simulation needed when dealing with physical interaction of virtual scenario emulating the remote scenario [43]. • To overcome "1 ms challenge" • Improved multiplexing model for video and audio together. • Enhanced perceptual performance in haptic telepresence system that improves transparency requirements.
Ultra-high Availability and Reliability of Information/ Connection	To ensure a consistent stream of information between server and end user. Relying on the data of the end user and its feedback.	• Making use of concurrent connections with several links [44]. • Using multi-path communication to avoid a single point of failure. • Relies on dynamics of the Channel State Information (CSI). • Need for re-exploring the control layer, transport layer protocols and session layer [45,46].
Network Slicing	Trade-off between the three generic services of 5G, viz. eMBB, mMTC and URLLC.	• Non-orthogonal allocation resources among the heterogeneous services through slicing of radio access network (RAN) [47]. • Dynamic network slicing for facilitating network in demand functionalities [48,49]. • Integration of network-aware and control-aware for maximising Quality of Experience (QoE). • Need for dynamic control switching methodologies for TI telepresence applications [50].
Wireless Resource Customisation	Usage of application-specific wireless resources allocation techniques.	• Need for joint uplink and downlink symmetric resource allocation with constant rate [51]. • Radio resource slicing, i.e., Flexible resource allocation techniques with network slicing [49] and adaptive flow management for traffic.
Easy Incorporation	Incorporation of wired and wireless system, i.e., hybrid systems.	• Incorporation of haptic communications in the 5G TI system. • Incorporation of Haptic codecs involving the kinaesthetic and tactile data.
Unlicensed Band	Undependability of freely available unlicensed band.	• To determine the trade-off between the RTT (delay) and energy efficiency in unlicensed band. • A traffic balancing scheme and scheduling needed [52]. • Collaborating licensed and unlicensed access keys in 5G unlicensed [53].
Safety and Security Concern	Regarding the data integrity and accountability.	• Imbibe the trade-off for the required security level with the increment in RTT (delay). So distinct levels of security would be opted across broad range of tactile applications [3].
Haptic Devices	Dealing with Haptic Sensor and Haptic Actuators.	• Optimising the spatial resolution, sensitivity, scan time and placements while selecting haptic sensors. • Designing a lightweight haptic display that gives an excellent feeling to user as similar as it would feel in the real-world context.

Table 3. *Cont.*

Challenges	Description	Potential Enabler and Solution with References
Kinematic Devices	Dealing with Kinematic Sensors and Kinematic Actuators	• With regard with post-processing time of reading data from sensors, algorithms are needed to be devised which will dynamically select the sensor and read the data. • Computational work is needed to push to the cloud for those with high orders of post-processing time. • Choosing physical actuators and driver circuits according to the use cases that help to minimise the RTT.

4.1. Transparency with the User

Reliable and susceptible communication is required when we are executing a task at remote distance. Therefore, the user needs to experience a specific level of immersion to deliver the desired activities when communicating remotely. These desired activities must be user-friendly in real time and be effectively executed in the remote environment to create the appropriate acknowledgement to the user. Without this non-cognitive transparency, the efficiency and authenticity of this communication loop cannot be guaranteed [54–56]. When a measurable round-trip time delay appears, complete transparency becomes nearly impossible. Additionally, there is a need for correct simulation of physical interaction when the user tries to mirror the virtual environment with the remote environment.

Another challenge is the transparency of the system being affected by lossy haptic data compression and communication delay. Thus, the perceptual dead-band-based kinaesthetic data compression approach could be used to improve the quality of learning for haptic teleoperation in a TI environment [57].

4.2. Round-Trip Time of 1 ms

To have an option to guarantee a transparent experience, the most challenging factor is to achieve a round-trip time (RTT) of 1 ms [3,58]. The motion sickness delay that occurs while performing any activity in one place, where another person perceives it in another place is called lag [59]. For haptic communication, various examinations demonstrate that lag will be observable if RTT is greater than 1 ms [60,61]. If this lag is noticeable, it influences transparency.

One of the crucial factors that affects the smooth flow of any haptic communication in a network is RTT. However, RTT is significantly affected by queuing and processing delays at the intermediate nodes and packet transmission times. The speed of light is among the most constraining elements for the RTT. Suppose the propagation time taken by the packet to reach a destination is more than 10 ms. Therefore, by considering the 1 ms challenge, the propagation time taken by the packet should be less than 1 ms. With 1 ms time delay constraint, it is workable for short-range communication.

With the availability of 4G mobile cellular networks, the RTT for short-range communication incurs a 15 ms delay, which cannot accomplish the necessity of 1 ms for a tactile response [60]. Furthermore, due to the evolution of 5G cellular networks, the RTT will incur $<$5 ms delay, which supports the necessities of haptic communication [61].

For haptic data communication, the packet size required should be less than 1500 bytes [56]. Taking all parameters such as transmission and processing delays into consideration, the RTT can be further minimised for smaller packet size data [58]. This is a step that we take closer to achieving haptic data communication with the challenge of 1 ms.

In addition, the essential point of interest is to execute the concept of the TI which supports infrastructure or architecture with RTT below 1 ms. 5G technology is still being explored and is not available to consumers. To satisfy the conditions of 1 ms, the control server and end-point device should not be placed at distant places as the end-user information needs to be executed immediately, and acknowledgement must be sent to the origin. Therefore, to avoid any delays, the control servers should be profoundly reliable and process all the end-user information.

Subsequently, to encounter the design concern for 1 ms RTT, one-way physical-layer transmission is empowered. Thus, the one-way transmission must have a minimum packet size and around the 100 μs duration. To accomplish this necessity, every packet cannot surpass a 33 μs packet duration [62]. The explanation for this is the need for additional structural delay that demands encoding, detection, and decoding at the transmitter and receiver ends. This restricts the packet size to less than 0.33 times the desired delay. Using the current LTE cell framework, the modulation used is not a feasible proposition, as the length of one OFDM symbol is nearly 70 μs long. A total round trip of the cellular physical layer is essential for the TI, possibly with 5G cellular networks.

4.3. Availability and Reliability of Information

It is expected that control servers must process and execute the end-user information frequently without any breakdown in the communication. Additionally, the communication path opted should ensure a reliable stream of information between the servers and end users. To ensure that there is no corruptive information, the processed data ought to be exemplified to guarantee that any threats or vulnerabilities will not have any access to the information [4].

4.4. Reliability of Connection

The reliability in communication relies on the data received from the end user and feedback to the remote place. If the data received is incorrect, then the same is carried forward to the remote place. The TCP and UDP protocols have their drawbacks, which are not reliable for this type of communication. Sadly, this protocol algorithm leads to undesired propagation delay, and it is not acceptable to have a communication based on real-time information [63]. Therefore, there is a need to design a highly reliable infrastructure that will support audio and video data, with a packet loss probability of maximum 0.001% [4]. Therefore, modifications are required for existing protocols [63], or a new protocol should be created that goes with the requirements of 5G [8].

4.5. Network Slicing

A network slicing technique is essential in accomplishing the framework for supporting the prerequisites of various applications. This technique arose with 5G mobile systems, but other application systems can also adopt this technique. The slice-specific customisation and performance isolation of resources could be done to effectively empower various applications and guarantee the effective usage of resources. Using these techniques, it is necessary to slice the network with core network resources and radio access.

Regardless of a lot of research on network slicing, various issues related to slicing require further analysis, including productive virtualisation of the network framework, applying services to network slice, the disintegration of network function, and end-to-end network orchestration, and management mechanism [64]. Without depending on the tedious architecture and protocol-level alternations [65], radio/remote resource slicing must be accomplished dynamically, which is an essential part of any network slicing resolution.

In addition, mission-critical IoT (mc-IoT) services have different requirements in terms of latency, availability, reliability, network resources, etc. The work done in [66,67] has not considered the network infrastructure that caters to mc-IoT's strict requirements. To address the above challenges, a flexible network infrastructure based on NFV was designed [68]. Depending upon the need for different mc-IoT applications, the services that guarantee slicing are deployed, and the network resources are distributed based on the shared physical infrastructure.

According to the 3GPP releases, there are three generic services under the 5G–New Radio (NR) framework that address new verticals and scenario deployments, as shown in Figure 8. The generic services are:

- Enhanced mobile broadband (eMBB): Mainly focusses on faster speeds for applications demanding higher rates.

- Massive Machine-Type Communication (mMTC): Mainly focusses on sensing and monitoring systems.
- Ultra-reliable low-latency communications (URLLC): Mainly focusses on providing very low latency for mission-critical systems.

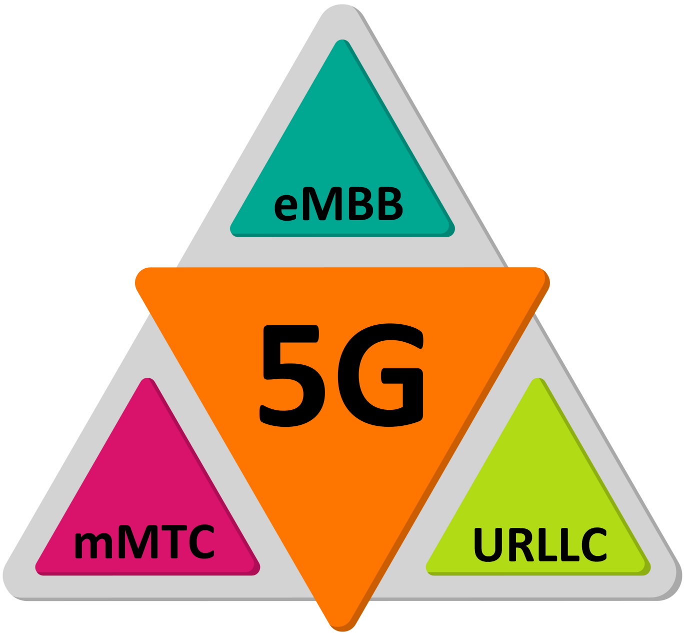

Figure 8. The three generic services offered by 5G.

In network slicing, the 5G framework is relied upon to oblige most devices that will interface with the network with a different Quality of Service (QoS) and Quality of Experience (QoE). It incorporates round-trip time (RTT), throughput, nature of information shared between the end devices and application servers, and frequency of data transfer [69,70]. The three generic services and their attributes are mentioned in Table 4.

Table 4. The three generic services under 5G framework and their attributes.

Attributes/Generic Services	eMBB	mMTC	URLLC
RTT	Moderately Low	Moderately Low	Extremely Low
Throughput	Moderately High/High	Moderately Low	Moderately Low/Moderate/Moderately High
Availability	Moderate	Moderate	Extremely High
Frequency of Data Transfers	Moderately High	Moderately Low	Moderately High

4.6. Control Co-Design

Two reciprocal standards are used to acknowledge control the application over the wireless system, i.e., network-aware control design and control-aware network design. Previously, the objective was to improvise network layer protocols to upgrade real-time execution. This modification holds as a piece of evidence for advancing work towards the TI. Subsequently, the design and configuration of control feedback codes are matched to the shortcomings of the communication medium. For the teleoperation framework, the structure of adaptive controllers [71] is a classic case of this modification. Thus, this modification needs to be closely associated with networks to mutually improve control-aware network design and network-aware control design.

To consolidate the dynamic nature of B5G networks, the RTT minimisation will always be a concern while having communication between master and slave sections. The rising timing requests are put on the control loop, thus causing a new challenge to reduce the overall RTT of the system. Hence, new approaches are needed to solve these RTT issues. However, the decoupling of the control loops can be done to make the two sections independent of each other by employing parameter weights on each side. Hence, incorporating the machine-learning or prediction models would be a potential solution to resolve the RTT issues in B5G networks [72].

4.7. Wireless Resource Customisation

To customise wireless resources, network slicing techniques can be used as an open door. Wireless resource customisation alludes to the usage of streamlined application-specific wireless resource allocation techniques within the assigned slice. Mostly, either human-related or machine-related communications are dependent on the traditional wireless resource allocation strategies. Such strategies may not be helpful for a TI application, but these traditional strategies mainly concentrate on the configuration of the uplink and downlink of tactile communication. Nevertheless, combined uplink or downlink configuration is alluring for an application considering the control loop [73]. Except for a few ongoing types of research [51,74,75], there are still loopholes (unexplored areas) of wireless resource allocation for TI applications.

Few works have been done to allocate resources with emerging technologies such as SDN, NFV, MA techniques, etc. The work in [76] focuses on understanding the traffic requirements of the TI environment, wherein strategies are discussed to control and allocate the bandwidth of the network. The standard FibreWireless (FiWi) infrastructure is merged with SDN to mobilise the bandwidth allocation. The SDN controller programmatically allocated the required resources based on the current global traffic status. Hence, the required QoS was also achieved under different TI environments.

4.8. Easy Incorporation

Regardless of the accessibility of high-end specifications of the wireless protocols, some hybrid systems probably exist, ranging from small to medium geographical areas. The goal of hybrid systems is to easily incorporate wired and wireless systems without affecting performance and efficiency. This kind of incorporation is accomplished through particular Internet-enabled devices. The problem of consistent incorporation has been researched in a few past investigations [77] which coincide with the introduction of wireless for modern systems. Nevertheless, a concise methodology is required to research this problem, as prior research may not be straightforwardly good with continuous tasks regarding Time-Sensitive Networking (TSN) and 5G-New Radio (5G-NR).

A teleoperation system was proposed based on the 5G-NR to examine and study the performance of haptics over Internet protocols [78]. The feasibility of the proposed system ensured reliable communication and did not violate the requirements of QoS.

4.9. Unlicensed Band and More

A significant number of wireless technologies work in the unlicensed band, i.e., 2.4 GHz to 5 GHz. There is a crowded situation regarding wireless technology's reliability within these freely available unlicensed bands. Because of this reliability, an examination was initiated to check for the substitute free spectrum for TI applications. With the availability of enormous bandwidth, millimetre waves (mm-wave) are especially appealing for TI [79]. Although mm-wave technology comes with a set of limitations and challenges for shorter-range communications, these issues also need to be taken care of [80].

Several finger augmentation devices are wired, and aim to recover lost human senses wherein the user has lost the ability to feel objects. Because of the wired system, it limits the free mobility of hand gestures and creates a feeling of being tied to some objects. These devices have an electronic surface and should be worn on the tip of the fingers. In [81,82], the radio-frequency finger augmented device (wireless) is considered to be a promising enabler for TI. This wireless system comprising of a reader worn on the wrist and a sensing tag worn on the fingertip makes use of an ultra-high frequency band ranging from

860 MHz to 960 MHz. Additionally, there are chances of impedance mismatch between the transmitting antenna and the electronic circuit, thus affecting the communication link. Self-tuning microchips address this issue. However, the concern remains regarding the distance between a transmitting antenna and an electronic circuit. If the distance is large between them, the tag will be disconnected and disrupt the normal functioning of the radio-frequency finger augmented device.

4.10. Safety and Security Concerns

Safety and security issues have been significant concerns for a wide range of information regarding the TI and its applications. Data integrity, reliability, and accountability must be catered for if we rely on the TI to facilitate daily applications and avoid any harm if it does not work appropriately. Depending upon the application and various types of information, various dimensions of security are required. If we consider the latest security advancement available today, haptic communication can take place over the network. However, there is a significant increase in RTT when using the current implementation of security. However, the requirement of security not only exclusively constrains access to information but also there is an issue of restricting the RTT. It entirely relies upon the application whether priority is given to the security or RTT. For instance, in a military organisation, information requires high privacy. On the contrary, some VR applications require minimal latency and lower requirements for the security of data. Subsequently, it can be concluded that there is always a trade-off for security and latency requirements depending upon the type of application.

Furthermore, to provide network coverage to catastrophically affected areas following events such as earthquakes, tsunamis, etc., potentially emerging technologies such as 5G, blockchain and drones can be adopted in a TI environment. Therefore, drones can be mounted with small cellular base stations to provide cellular services in affected areas. The main challenge is to have data security in such flying cellular base stations. To tackle the concerns about data security, the blockchain-based framework [83] was used to provide a security layer in the communication between (1) drone to drone and (2) user to the drone.

4.11. Challenges Related to Haptic Devices

There are also challenges related to the sensors and actuators at operator and teleoperator ends. Related to haptic devices, haptic sensors and actuators are used for communication. These sensors are usually mounted at the teleoperator end, which is used to sense the tactile data. It also senses the activity going on at the teleoperator end and is relayed back to the operator/user end as feedback. The haptic actuators handle the feedback process, often known as haptic feedback devices.

4.11.1. Haptic Sensors

Haptic sensors are useful for detecting pressure for a delicate body, body control, and for the worst-case control scenario of <10 kPa, 10 kPa to 100 kPa and 325 kPa, recognisable to humans [84,85]. There are different methods to measure pressure. The most famous methods are resistive and capacitive. In the resistive method, the material used is pressure sensitive and is used to create a sensor [86]. In the capacity method [84], the capacitance difference is noted using a dielectric material between two conducting plates. Then the difference in capacitance is then converted and digitised to measure pressure.

The dielectric material used for capacitive haptic sensors is the elastomer polydimethylsiloxane (PDMS), famously called silicone. PDMS features include (i) excellent dielectric constant, (ii) low young's modulus, and (iii) very flexible placement of sensors. However, there are some different non-idealities in PDMS pressure strain sensors, thus making the structure complicated. The non-idealities include creep unwinding, hysteresis, and so on. Thus, the need to design the capacitive weight sensor is taken into account by considering all non-idealities of PDMS.

Another vital parameter to consider in building the capacitive sensor is sensitivity. Sensitivity comes into play whenever there is a change in pressure. When the sensor's sensitivity is high, the sensing process, conversion time and the sensor's estimation scope are reduced because of saturation effects. Therefore, the trade-off is if the blend of the high and low sensitive sensor is considered, the fabrication process becomes more tedious and thus increases its fabrication cost. In addition, PDMS can also be modelled to adjust the sensitivity range of the sensor. Nevertheless, the model will also add complexity and cost to the fabrication.

When it comes to designing the haptic framework, a commonly neglected factor in the literature is the placement of sensors. There are two ways in which haptic sensors can be fabricated: (1) single-element sensor and (2) multiple-element sensor arrays [87–91].

However, single-element and array sensors are commonly expensive. Therefore, these sensors must be placed in the detection zone to increase the coverage radius with the correct placement techniques. The increase in array size is directly proportional to the scanning rate of the number of sensors. Thus, the overall consumption of power and the time required for sensing are incremented. There will always be a trade-off between spatial resolution and the coverage area. Subsequently, the chances of collaborative design of the single-element and array sensors are more likely achievable. However, these designs could make the placement of sensors tedious.

There is an advancement issue to investigate [90] about the conceivable arrangement to have various sensing circuit-handling sensors in different areas of the array sensor. Hence, finishing up construction of a haptic sensor for applications of the TI is not a straightforward process. There are many challenges that need to be resolved, including scanning time, placement of the sensors, spatial resolution and sensitivity.

4.11.2. Haptic Actuators

There are two types of haptic feedback present in the TI system [92,93]: (1) tactile touch and (2) kinaesthetic touch. Tactile touch is touch perceptible by human skin, for example, pressure, force, friction, vibration, texture, and skin temperature. In contrast, kinaesthetic touch is the feeling of a neighbouring body part's general position and pressure related to the muscle tension.

Throughout the years, there has been a tremendous increase in the research of haptic feedback, where it is challenging to construct or design a haptic feedback framework. This challenge expects a sense of touch to be delivered to the user as they feel it in reality. But it should be noted that haptic feedback does not fundamentally convey the realistic sense of touch and a limitation is that it does not imply actual touch.

In Reference [94], the authors performed an experiment where users try to identify texture using tactile gloves and a custom-built haptic device. The experiments showed that tactile gloves reasonably recognised the texture. Depending on the desired use, haptic feedback can be conveyed in numerous forms. Experimentation has been done on numerous haptic displays with user and haptic feedback. The results vary from the non-contact tactile display, e.g., displays using the radiation effect on ultrasound [95], to feeling vibrations on fingertips using vibrotactile gloves [96–99]. However, there is a limitation with non-contact displays where the display area is barely movable. Hence, this limitation gives rise to a scalability problem where the end user is restricted from moving around freely in a given area.

There is another dimension for research regarding the dependency on gloves-based display. This type of display is non-grounded, which means it can freely move around. It is not tied to any heavy equipment to limit the free movement of the display. However, this display lacks kinaesthetic feedback.

In remotely operating systems, instead of the virtual system and because of limited kinaesthetic force feedback, the user will virtually experience holding, thumping, squeezing, or moving objects. This happens because of excessive force at the remote system. This might result in a limitation or complete prevention of the movement. There is another dimension for the perception of the weight of the object [100].

The recent implementation of glove-based haptic displays includes kinaesthetic feedback often restricted by the region of working space. This happens due to the glove being linked to the user's arm, or the entire system being grounded, e.g., in [100]. In addition, ungrounded trails are carried out with a glove-based haptic display where the system algorithm makes gloves too heavy for further testing. Thus, this process is more time-consuming.

From the examination discussed above, there is no fixed or a total solution for kinaesthetic feedback yet. A trial demonstration is mentioned in [98] where tests have recognised friction, weight, pressure, smoothness, and hardness with the help of gloves with only vibrotactile feedback. Nonetheless, it was quite different making identifications in one place compared to achieving the same with a remote object. Because of these adverse effects, we require sensible recognition to create real kinaesthetic feedback.

The design of a real kinaesthetic display will have current challenges, including tactile and kinaesthetic feedback, where displays are not attached to any ground and can move around freely. Another idea is to have a lightweight system at the same time. For some applications such as telesurgery, a haptic display would not be helpful. In such cases, a replica of the remote and the real-life scenario could be developed so that realistic feedback mechanisms will solve the problem.

4.12. Challenges Related to Kinematic Devices

There are also kinematic devices that are responsible for the activity happening at the operator and teleoperator end. They catch or track movements of the operator and reproduce the same at the teleoperator end. Based on these devices, there are also kinematic sensors and kinematic actuators. Kinematic sensors capture the movements at the operator end, while kinematic actuators reproduce the same at the teleoperator end.

4.12.1. Kinematic Sensors

There are different types of sensors available for capturing or tracking the movements at the operator end. We will discuss a few of the approaches that are being used to devise kinematic sensors. Simple mechanical frameworks are adopted to capture the moment and are generally equipped with some connections and electrochemical transducers such as a potentiometer to follow the motion. There are also other methods for tracking the movements of the body such as [101–106]: (a) Magnetic-based strategy is used wherein magnetic sensors are deployed at different parts of the body and as the body moves, the sensor tracks the movement of the body and records its position; (b) In radio-frequency identification (RFID)-based strategies, the radio-frequency tags and sensors are used to gather the movements of the body; (c) Image sensors are also strategised to catch an image at stipulated period, and then it is processed to evaluate the position/motion of the body; (d) Capacitive-based techniques are also used to capture the body movement with the deployment of capacitive sensor arrays, placed in proximity to the body. Here, a parallel plate of the capacitance concept is used between the body and sensors, noting a change in capacitance as the body moves, and many more. Many recent techniques have been developed to sense and track the movement of the body at the operator end.

Despite possessing such techniques, there are always some limitations regarding the recreation of the movements at the teleoperator end. Moreover, many are helpful in catching just motion [105,107,108]. This is not helpful in haptic frameworks where the operator movement is to be steadfastly followed and replicated. Even though these strategies can be used to track movements, such attempts will give coarse information focussing on the movement being detected.

Although these strategies execute admirably in a few haptic cases, they fail when the user handles the duplication of the remote activity. There will also be a limitation for image sensors where it demands the operator focus on the sensors, which restricts the working zone of the user. This imaging strategy also experiences the blockage of the blood vessel, resulting in the loss of free movement, gripping, etc.

Notwithstanding a couple of exceptional cases, there are a few strategies such as capacitive, magnetic and RFID-based strategies, which request the operator to connect sensors as wearable gadgets. Wearable gadgets such as tactile gloves can be developed with necessary sensors to track or capture the operator's motion using such strategies. In addition, a similar glove can likewise consolidate haptic actuators to facilitate haptic feedback. On the contrary, it can be awkward to wear glove-based gadgets in certain use cases.

Another significant thought to be considered is the output time or scanning time. This additionally incorporates the time it takes to scan and track the operator kinematic movement. If multiple sensors are present in the TI system, each individual sensor will have its scan time constraint, and processing it could be a challenge to achieve 1 ms TI constraint. Because of the limitations of sensors that support low baud rate embedded protocols to transfer the sensor information, this forces the master section to seek sensor information, each one in turn. This seeking time can add up to the general output time of the kinematic strategy. A solution here is for the device calculation to powerfully pick the sensor of intrigue and dynamically read the information instead of scanning the sensor one at a time or in a stipulated sequence. Therefore, more research is required to solve this problem.

As discussed above regarding processing time or scanning time, still kinematic strategies adopt refined kinematic algorithms to capture movement. These algorithms contribute to more processing time. Therefore, conceivable arrangements can be adopted by computing all the information in the cloud.

4.12.2. Kinematic Actuators

Kinematic actuators are used at the teleoperator end. Here, a robot will be placed at the teleoperator end to copy the action from the operator. However, there could be a variation in the Degrees of Freedom (DoF) of movement between an operator and a robot. In such instances, the reverse version of kinematic equations is applied. These equations calculate the link angle of the robot to guarantee that the final stance of the robot intently resembles that of the operator.

The reverse versions of kinematic equations are responsible for solving basic kinematic conditions for robot links. If the number of robot links increases, these kinematic equations fail and become tedious to unravel. Therefore, numerical solvers are computationally concentrated, which can increment the activation time and therefore increment the RTT. Subsequently, one solution could be to transfer all the computational work to the cloud and save computational time.

5. Review of Related Articles

To formulate this survey paper, relevant TI-related articles contributing to 5G, SDN, NFV, Cloud/Edge/Fog Computing, Multiple Access and Network Coding are reviewed and investigated to realise TI. These articles are selected from several refereed journals, conference proceedings and white papers obtained from credible and well-known databases such as IEEE Xplore, ScienceDirect, Springer, and ACM. We carried out an extensive analysis and synthesis of research findings to make a meaningful conclusion. Table 5 provides a review of the related articles on the TI for enabling technologies.

5.1. The Potential of the Tactile Internet

In a characteristic advancement to various Internet encapsulations, thoughts of the TI [4] are rising in which ultra-responsivity and ultra-reliability will empower the remotely operated real-time control and physical haptic communications. The TI will include a new area of measurement of human and machine interaction through constructing interactive and intelligent frameworks. The TI will facilitate a genuine change in outlook from content-delivery to skillset-delivery networks and, subsequently, change every part of society. As of now, the Institute of Electrical and Electronics Engineers (IEEE) and European Telecommunications Standards Institute (ETSI) [109] standards are also incorporating standardised activities for the TI.

Table 5. Review of related articles on TI for enabling technologies (5G, SDN, NFV, Cloud/Edge/Fog Computing (CC/EC/FC), Multiple Access (MA), and Network Coding (Net. Cod.)).

Authors	Year	5G	SDN	NFV	CC/EC/FC	MA	Net. Cod.
Cheng et al. [31]	2020	✓	×	×	✓	×	×
Mekikis et al. [110]	2020	✓	✓	✓	×	×	×
Sharma et al. [111]	2020	✓	✓	✓	✓	✓	✓
Gokhale et al. [112]	2020	✓	✓	×	×	×	✓
Na et al. [113]	2020	✓	×	×	×	×	×
Zhani and ElBakoury [114]	2020	✓	✓	✓	✓	×	×
Meshram and Patil [115]	2020	✓	✓	✓	✓	×	×
X. Wei et al. [116]	2019	×	×	×	✓	×	×
I. Budhiraja et al. [117]	2019	✓	×	×	×	✓	×
Vora et al. [118]	2019	✓	×	×	✓	×	×
Ge et al. [68]	2019	✓	×	✓	×	×	×
Aggarwal and Kumar [119]	2019	✓	✓	✓	✓	×	×
Fanibhare et al. [120]	2019	✓	✓	×	✓	×	×
Maier and Ebrahimzadeh [121]	2019	✓	×	×	✓	×	✓
Arshad et al. [122]	2019	✓	×	×	✓	×	✓
Jinke Ren et al. [123]	2019	×	×	×	✓	×	×
Kim et al. [6]	2018	✓	×	×	×	✓	✓
Grasso and Schembra [49]	2018	✓	×	×	×	×	✓
Alextian et.al [124]	2018	✓	✓	×	×	×	×
J. Cabrera et al. [125]	2018	✓	✓	✓	✓	×	✓
Dmitry et al. [126]	2018	×	✓	✓	×	×	×
Y. Xiao et al. [127]	2018	×	×	×	✓	×	×
Ateya e al. [128]	2018	✓	✓	✓	✓	×	×
S. Troia et al. [129]	2018	×	✓	✓	×	×	×
C. Grasso et al. [49]	2018	✓	×	×	×	×	×
Li et al. [130]	2018	✓	×	×	×	✓	×
M. Gharbaoui et al. [131]	2018	✓	✓	✓	×	×	×
Popovski et al. [47]	2018	✓	×	×	×	✓	✓
Chatras et al. [132]	2017	✓	×	✓	×	×	×
Yi-Wei Ma et al. [133]	2017	×	✓	✓	✓	×	×
T. Theodorouan et al. [134]	2017	×	✓	×	×	×	×
K. Wang et al. [135]	2017	×	✓	×	×	×	×
Ateya et al. [136]	2017	✓	×	×	✓	×	×
Feng et al. [137]	2017	✓	×	×	×	✓	×
Pilz et al. [138]	2016	✓	✓	×	×	✓	×
Athmiya et al. [139]	2016	×	✓	×	×	×	×
Intharawijitr et al. [140]	2016	✓	×	×	✓	×	×
Simsek et al. [141]	2016	✓	✓	✓	✓	✓	✓
Maier et al. [8]	2016	✓	✓	✓	✓	✓	✓
Tong et al. [142]	2016	✓	×	×	✓	×	×
N. Truong et al. [143]	2015	×	✓	×	✓	×	✓
P. Iovanna et al. [144]	2015	✓	✓	×	×	×	×
D. Szabo et al. [145]	2015	✓	✓	×	×	×	✓
F. Bonomi et al. [146]	2011	×	×	×	✓	×	×
Cuervo et al. [147]	2010	×	×	×	✓	×	×

Furthermore, at the wireless edge, 5th-generation mobile communication systems are essential to support the TI. A research project has been carried out at the Mobile and wireless communications Enablers for the Twenty-twenty Information Society (METIS) [61] along with the telecommunication industry Next-Generation Mobile Networks (NGMN) alliance [148] regarding the early evaluation of 5G scenarios. Dealing with the TI, there has been an increase in new requirements and challenges for designing of 5G network [130].

As of late, thoughts of the TI [4] has risen, which is imagined to give a change in perspective by empowering wireless networks for ongoing steering and control communications. The working group with a standard as IEEE P1918.1 [11] refers to the TI as a metadata set of networks, mainly for accessing the data wirelessly, receiving, manipulating, or managing real and virtual data, thus processing in perceived real time.

5.2. SDN-Based Design

SDN is a new concept in networking that facilitates a dynamic, flexible, and cost-effective system structure by physically partitioning the data forwarding plane and control plane. The control plane handles a suitable choice to deal with traffic, whereas the data plane takes care of forwarding the traffic according to the control plane. SDN grants permission to the system operator to design, configure, control and deal with the system through programming software such as application programming interfaces (APIs). SDN is mainly used to disentangle the system hardware and increase network adaptability.

Gharbaoui et al. [131] presented a service-chaining orchestration framework comprising dynamic virtual function (VF) selection and intent-based traffic-steering control competencies to upgrade Management and Orchestration (MANO) framework parts with latency-minimised and self-adaptive service-chaining highlights over geographically distributed SDN-based cloud data-centres (DCs) interconnected through a SDN Wide-Area Network (WAN). Furthermore, Yi-Wei Ma et al. proposed a software-defined infrastructure (SDI) [133] with NFV, which is then deployed in an Industry 4.0 network environment. This infrastructure uses the technological concept of SDN and NFV, which enhances the overall activities of the network environment, the rate of information transmission and the QoS provided.

On similar lines, Sebastian Troia et al. [129] presented their work on the SDN/NFV Orchestrator, a new service orchestrator called SENATUS. It facilitates a service orchestration for network segments deploying Openstack as infrastructure manager and Open Network Operating System (ONOS) as SDN controller. Moreover, Theodorouan et al. [134] proposed an SDN solution for wireless sensor networks (WSNs) which (i) uses intelligent centralised control mechanisms to adjust the protocol operations dynamically; (ii) underpins versatility to difficult prerequisites of the WSNs; (iii) keeps an adapted architecture; and (iv) shows enhanced network management and operation regarding execution and resource use. In addition, Christian Grasso et al. [49] proposed an architecture for unmanned aerial vehicle (UAV)-based video surveillance with TI constraints, where the drone-based Markov chain model is examined.

Various methodologies talk about using SDN at the central network of the cellular framework. In addition to working towards the TI, the need to code the system is incorporated with SDN to minimise the RTT in the 5G framework. A software router within the network is encrypted, and acts as a virtual network function (VNF). They are mainly worried about coding and SDN, but they have not considered mobile-edge computing (MEC). This framework is predominantly presented for 5G as well as IoT [117].

A 5G-based SDN infrastructure is presented in [135] with the massive deployment of small cells. Therefore, having an idea of small cells incurs difficulties of continuous handover and delay during the handover process. Here, the authors have facilitated a framework to defeat these difficulties by incorporating an SDN controller at the central system. By deploying an SDN controller, the framework is ready to anticipate that the end user or a client is moving and subsequently can deal with the handover process in less time, by characterising three sorts of program interfaces. Since the fundamental thing of the TI framework is to meet 1 ms round-trip time, i.e., ultra-low latency, cognitive control ought to be conveyed at the central network to accomplish desired RTT.

Taking SDN architecture into consideration for ultra-reliable and ultra-low-latency communication, Alextian et al. [124] have introduced Residue-Defined Networking Architecture (RDNA) as a unique strategy for enabling critical competencies of micro-datacentre networks. This architecture is built on the concept of SDN to meet complex and stringent demands from next-generation networks.

In addition, the work in [125] by Juan Cabrera et al. featured the significance of SDN and NFV for 5G communication along with TI applications. It describes that SDN and NFV complement each other and facilitate empowering technologies to have facilities such as computing, storage, and networking functions. Furthermore, Dmitry et al. [126] proposed an effective algorithm and software for virtual slice formation in SDN dependent on the information of base network and links connectivity information.

5.3. FC-Based Design

FC was originally proposed by Flavio Bonomi, vice president of a network device manufacturing organisation called Cisco in 2011 [146]. FC can be explained as a highly virtualised platform where an enormous number of heterogeneous, pervasive, and decentralised devices connect and correspond to other devices. These devices provide computation, storage, and networking services between and devices and conventional cloud centres, but not precisely at the edge of the networks, without the interference of third parties.

The capabilities of cloud computing and services are extended to FC, where routers, gateways, switches, etc., can also be a part of the network with all properties of FC. It was fundamentally used for the automation of types of equipment since FC has a background in IoT.

In Reference [127], Xiao et al. focussed their research on an energy-efficient design of fog network that helps to have low-delay-supported TI applications. Here, they have explored the performance parameters such as service reaction time of the end clients and power use efficiency of fog nodes. Additionally, a novel cooperative FC concept is presented with fog nodes with various processing and energy resources to coordinate with one another. This led to fulfilling the objective of balancing the workload or the request executed by multiple fog nodes.

The idea of edge-assisted cloud computing and its connections is related to the developing area of FC. Such frameworks use low power and efficient embedded computers to facilitate nearby processing close to end users or the cloud. The Fog of Things (FoT), analogous to Fog Computing (FC), alludes to the amalgamation of various fog nodes that could be connected and communicated with each other with IoT.

The FC has a decentralised computing structure dependent on FC nodes (FCNs) and can be fixed at any architecture location between the end-user device end and the cloud. With FCNs that use M2M gateways and wireless router devices, FC acts as a computing layer between the end device and the cloud layers. These FCNs are used to process and store information from end-user devices before sending it to the cloud.

Nonetheless, the hypothetical establishments for advancing distributed FC systems to satisfy TI needs are still deficient. Specifically, computationally escalated services needing low delay usually consume more energy from fog nodes. Simultaneously, many TI applications include lightweight equipment such as drones, robots, and vehicles with constrained power supplies.

The International Telecommunication Union (ITU) and Next-Generation Mobile Networks (NGMN) alliance recognise FC as one of the crucial factors for the TI to accomplish ultra-low service delay for clients [8,141,148]. Rather than cloud data-centres (CDCs), fog nodes can be deployed near the end clients so that the task transmission delay can be substantially diminished. However, because of each fog node's limited computational or processing ability, carrying out a considerable number of tasks to fog nodes will bring about a high processing delay. Therefore, previous works have discussed the most efficient resource provisioning of fog nodes to decrease the processing delay. For instance, a virtual machine (VM) synthesis technique is presented to enable each end client to rapidly arrange the resources of neighbouring fog nodes and make the required VM images achieve the desired TI application.

Furthermore, Cuervo et al. [147] presented a framework that permits fine-grained energy-aware offloading of client mobile codes to the system. Therefore, the topic of tactical cloudlets is explored for resource provisioning and, the provisioning component is introduced for the system to help processing, offloading and data staging at the tactical edge.

As far as the architectural aspects of FC are concerned, Bonomi et al. [146] exhibited one of the primary tasks of FC surveying the appropriateness of FC for the IoT. They mention the necessities of developing the application as far as real-time user communication, awareness of the location and the requirement for geo-distributed end nodes, and FC attends to these problems.

The authors have contributed more knowledge into the appropriateness of FC for IoT applications with a couple of use cases, including smart wind farms and intelligent traffic light systems in the accompanying paper [149]. Furthermore, V. Fanibhare et al. [120] proposed a multi-level cloud structure where the traffic flows over the cloud units efficiently to reach the slave section from the master section in TI system, to reduce unnecessary waiting times.

Along similar lines, a multitier infrastructure [142] is introduced in which edge cloud servers are differentiated into various level as per their separations to the edge. If the task on the edge cloud server of a given level surpasses its computational limit, the additional outstanding task is sent to a higher-level service. One of the FC areas is that many fog nodes are distributed and deployed over vast geographical territory. Nonetheless, this can bring about a noteworthy increment in energy consumption.

Moreover, Truong et al. [143] influenced the distributed approach of fog nodes to enhance awareness of the location in Vehicular Ad hoc Networks (VANETs). They tested their framework to the application case of lane-changing assistance. Additionally, they used the fog layer's services to execute and find an optimal parking spot, where the aggregated data were gathered from different fog devices, demonstrating the concept of the distributed idea of fog devices.

In Reference [150], an adaptive energy scheme was developed for fog nodes to work at various transmit powers with variable data rates. Jalali et al. [151] correlated energy consumption of applications using centralised (CDCs) with applications employing nano data-centres under the FC infrastructure. Xuejiang Wei et al. [116] proposed a new fog-based sensor cloud architecture for IoT. They facilitated the fundamental ways for physical sensor virtualisation, dynamic provisioning of virtual sensor group and service instance for key issues. Furthermore, Jinke Ren et al. [123] explored the joint communication and computation resource allocation to minimise the weighted-sum delay (RTT) of all devices in a cloud-edge collaboration system.

In summary, the advantages of FC compared to traditional cloud computing are featured in [152,153]. In Reference [154], the programming framework is designed to deliver resources to numerous IoT end-user devices by considering mobile FC. Therefore, at the primary level within FC, the examination has been accomplished for resource allocation with the FC framework.

Finally, FC has its capabilities and competencies as follows. It has location awareness and can be located at the edges of a network. It incurs low latency, which supports large-scale complex sensor networks and storage capabilities in a wide-area distributed network. Network faults can be analysed online and be integrated with the back-end cloud system.

6. Summary of Challenges

TI applications such as self-driving vehicles, augmented reality (AR), virtual reality (VR), Industry 4.0, immersive virtual reality (IVR) and eHealth are the hot topics of research, and a remarkable amount of research is being carried out. Still, existing network infrastructures are finding it hard to cope with the stringent requirements of the TI. Moreover, the speed of light also hampers the speed of TI communication as tactile ends can be at a maximum of 150 km from each other, otherwise there would be noticeable motion sickness, also referred to as lag.

As TI applications mentioned earlier, the demand for the core competencies such as ultra-low latency, ultra-high reliability, ultra-high availability, ultra-responsive and ultra-fast reaction times shows that current cellular infrastructure cannot support these competencies. It is worrisome to fulfil all the requirements of TI applications at the early stage of 5G development.

The challenges related to haptic devices such as Sensable [14] and Geomatic [15] in the market have a robotic arm attached to a stylus, which restricts the free movement of the arm. Thus, it reduces the Degrees of Freedom (DoF) that are required to realise the TI truly. Since there has not been significant development of the 5G framework, the consensus implies adapting one network and sharing the resources among various vertical applications.

Challenges are also experienced with the transparency of the user. An action executed in one location must replicate in remote locations with a specific level of immersion. If the RTT becomes noticeable or measurable, the transparency of the user is affected drastically. The RTT of haptic communications should be 1 ms or below. If this RTT is not achieved, it again influences the transparency of the user. There is another challenge between the control server and user to have a reliable stream of data so that any vulnerabilities cannot mess with the original data. The reliability of the connection also relies on the end-user data and its feedback.

Furthermore, there is a need for qualitative and quantitative research on network slicing, including the productive virtualisation of the network framework, applying services to the network slice, the disintegration of network function and end-to-end network MANO. Here, the concept of SDN and NFV would be helpful as a potential enabler to address the challenges of TI communication. Network slicing can be used to customise wireless resources. However, human-related or machine-related communications rely on the conventional wireless resource allocation strategies focussing on the uplink and downlink of the communication. Therefore, more research is needed for wireless resource allocation for applications, considering the global control loop required for TI applications. Thus, incorporating hybrid systems, including wired and wireless systems, could solve the challenges of examining and studying the performance of haptics over Internet protocols.

Because of the freely available unlicensed band, there was a crowded situation surrounding the reliability of wireless technologies. To address this issue, research should be conducted to find the substitute free spectrum for TI applications. Though millimetre wave could solve the TI's problems, it comes with a set of limitations for the shorter range of communications. In addition, there is always a trade-off between security and RTT requirements. A few applications require high privacy of data, and others rely on low RTT. Hence, emerging technologies such as 5G, Blockchain, etc., can be adopted in the TI scenario to resolve security issues.

Regarding haptic devices, there are challenges related to dielectric material used in fabricating sensors, power consumption, the placement and the sensitivity range of the sensor, scanning time, spatial resolution and much more. Moreover, there are challenges surrounding the realisation of the realistic sense of touch through haptic feedback. Since haptic devices cannot move freely and are grounded, scalability would annoy the user in a given area. More work is also needed to increase the DoF. Regarding kinematic devices, there are always some issues in replicating fast actions from master to slave sections. Therefore, refined kinematic equations or algorithms are required to capture the activities of the master section. On the other hand, applying reverse kinematic equations becomes more complex for unravelling and following the actions of the master at the slave sections.

If TI challenges are addressed or solved, the TI will open a new direction for novel applications, gadgets, and services. With the help of technological advancements, eventually, people will adopt emerging technologies, and thus we can make a better life in the society and on the planet.

7. Conclusions and Open Research Issues

A comprehensive review of the Tactile Internet (TI) is provided in this paper. This research has explored TI design aspects with the proposed application-centric design architecture and applications. In addition, an in-depth discussion of key applications with proposed illustrative diagrams of use cases and current issues and challenges with potential enablers of the TI are provided. Finally, an extensive review of the related articles on enabling technologies such as 5G, SDN, NFV, Cloud/Edge/Fog Computing, Multiple Access, and Network Coding is presented, keeping in mind that the importance of 5G network design, edge/fog computing, 1 ms RTT, compatible tactile gadgets, core software networking and artificial intelligence competencies come at the leading edge of research challenges.

The various epitomes of the Internet will be predominated by the rise of the TI that will probably bring real-time control and tactile experiences operating from a remote distance. TI facilitates a new transformation and development in wireless communication for real-time and virtual applications. It will transform pretty much every portion of the general population such that they become familiar with TI services. It is forecasted that cutting-edge 5G network frameworks will support the TI at the wireless edge.

Three possible future research directions and open issues regarding TI are outlined below: (i) traditional cloud-based computational techniques are adding up to the communication delay in wireless links due to the non-presence of cloud infrastructure near the end user. Therefore, the concept of Edge/Fog computing could be used to bring computational capabilities nearer the end user, and thus would be proved as a promising technology to reduce the RTT compared to the traditional cloud-based infrastructure; (ii) Due to requirements of high data rates and dynamic orchestration of resources in the core network and radio access network (RAN), the concept of network softwarisation in 5G networks would be the potential technology to guarantee end-to-end reliability and meet the less than 1 ms RTT requirement. Thus, to further improve RTT, emerging latency minimisation techniques such as SDN-based and NFV-based design could be the enabling technologies for the core architecture of RAN; and (iii) In a wireless system, various protocol layers take part in the overall RTT. Some fundamental delay components such as transmission delay and queuing delay should be considered in TI implementation. Therefore, effective physical and MAC-layer techniques are needed to improve RTT in the wireless transmission system.

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Appendix A. List of Abbreviations and Definitions

Abbreviation	Definition	Abbreviation	Definition
4G	4th Generation	MEMS	Micro-ElectroMechanical System
5G-NR	5th Generation-New Radio	METIS	Mobile and wireless communications Enablers for the Twenty-twenty Information Society
API	Application Programming Interface	MIT	Massachusetts Institute of Technology
AR	Augmented Reality	mm	MilliMetre
B5G	Beyond 5th Generation	MTC	Machine-Type Communication
BS	Base Station	NFV	Network Function Virtualisation
CDC	Cloud Data Centre	NGMN	Next-Generation Mobile Network
CPS	Cyber-Physical System	OFDM	Orthogonal Frequency Division Multiplexing
CSI	Channel State Information	ONOS	Open Network Operating System
D2D	Device-to-Device	PDA	Personal Digital Assistant
DC	Data Centre	PDMS	PolyDiMethylSiloxane
DoF	Degree of Freedom	POL	Passive Optical Local Area
DSI	Digital Senses Initiative	QoE	Quality of Experience
EDGE	Enhanced Data Rates for GSM Evolution	QoS	Quality of Service
ETSI	European Telecommunication Standards Institute	RAN	Radio Access Network
FC	Fog Computing	RDNA	Residue-Defined Networking Architecture
FCN	Fog Computing Node	RFID	Radio-Frequency Identification Device
FDA	Food and Drug Administrator	RTT	Round-Trip Time
FiWi	FibreWireless	SDI	Software-Defined Infrastructure
FoT	Fog of Things	SDN	Software-defined Networking
GPRS	General Packet Radio Services	TI	Tactile Internet
H2H	Human-to-Human	TSN	Time-Sensitive Networking
H2M	Human-to-Machine	UAV	Unmanned Aerial Vehicle
HSI	Human–System Interface	UE	User Equipment
IEEE	Institute of Electrical and Electronics Engineers	UMTS	Universal Mobile Telecommunications Service
IoT	Internet of Things	UX	User Experience
IT	Information Technology	V2I	Vehicle-to-Infrastructure
ITS	Intelligent Transport System	V2V	Vehicle-to-Vehicle
ITU-T	International Telecommunications Union-Telecommunication Standardisation Sector	VANET	Vehicular Ad hoc Network
LAN	Local Area Network	VF	Virtual Function
M2M	Machine-to-Machine	VM	Virtual Machine
MA	Multiple Access	VR	Virtual Reality
MAC	Medium Access Control	WAN	Wide-Area Network
MANO	Management and Orchestration	Wi-Fi	Wireless-Fidelity
MEC	Mobile-Edge Computing	WSN	Wireless Sensor Network

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