Discover Internet of Things

Review

Multi-sensory data transmission using 5G and B5G enabled network for healthcare: survey

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Abstract
The study investigates the feasibility of utilizing 5G and its future iterations (B5G) networks for the transmission of multi-sensory data, including audio, visual, haptic, olfactory, and gustatory data. The advent of 5G and B5G technologies has enabled the transmission of a wide range of sensory information in real-time or near real-time, thanks to their exceptional speed, low latency, and large capacity. The idea behind this review is to explore the technological developments that facilitate the transmission of data, such as layered protocols. This article aims to provide an overall survey and use cases for sensory data transmitted using 5G and B5G networks. The objective of this survey is to focus on challenges for multiple sensor data transmission using 5G and beyond network technologies, as well as how significant is to receive this information without losing them. Moreover, it tackles the inherent difficulties associated with guaranteeing adequate bandwidth, minimal latency, high quality of service, and robust security for the transmission of multi-sensory data via wireless networks. The goal is to provide an introductory overview for researchers, engineers, and practitioners who are interested in exploiting 5G and B5G networks to leverage the revolutionary capabilities of multi-sensory data transmission. The future scope at the end also highlights how to add enhancement in this field.

Keywords Telerobotics · Healthcare · Multi-sensory data transmission · 5G and Beyond 5G network

1 Introduction

"B5G" refers to "beyond 5G" or "6G" connections that address 5G network restrictions and enable multi-sensory data transmission. B5G networks should improve the processing of sensory data like timestamps, identity, and geographical mapping. These networks should facilitate intelligent device connections and provide essential network automation and optimization services. B5G networks address 5G network challenges such as terminal device power consumption, coverage, and network instability. Innovative tiny cells combined with 5G technologies should make B5G networks cost-effective. To satisfy the needs of a connected world, B5G network research explores novel technologies and network topologies. Non-orthogonal multiple access (NOMA) is a proposed B5G wireless network design to support more users and connectivity needs. True-data testbeds for 5G/B5G intelligent networks are being built by integrating sensing, communication, big data, and AI. These testbeds collect, store, standardize, and analyze enormous amounts of genuine network data to develop and validate B5G and 6G network technologies.

Telerobotic operations and robotic surgery benefit from 5G and B5G networks' faster data transmission, latency, and dependability [1]. 5G networks in some countries have enabled remote robotic surgeries and telemonitoring, allowing

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doctors to perform procedures and provide expertise remotely. The use of 5G technology in robotic surgery could save travel time and treatment delays for cancer patients. Notably 5G networks can offer remote surgeries with low latency and fast data transmission speeds, allowing surgeons to control remote machines from anywhere.

5G technology improves communication across a large sensor network, enabling predictive maintenance of production machinery and robotics. It also allows remote patient monitoring and diagnostics. New 5G networks and improvements enable an open system architecture that is mostly software-based and coupled with cloud infrastructures. According to the International Telecommunication Union—Radio Communication Sector (ITU-R), 5G networks and subsequent generations aim to support a few core services, known as traffic classes, with different requirements and attributes using a shared physical infrastructure.

Industry 5.0 monitors and analyzes healthcare applications in real-time using wearable devices and WSNs (Wireless Sensor Networks). Haptics include kinesthetic (forces, torques, location, velocity, etc.) and tactile (surface texture, friction, etc.) perception. The human sense of touch is tactile. In "Tactile Internet," an ultra-low delay Internet connection is needed for 5G use cases like haptic communication. Haptic communication employing networked teleoperation systems must efficiently and quickly exchange kinesthetic or tactile information while simultaneously providing audio and visual information, which is one of the uses of Tactile Internet.

A bilateral teleoperation system for a soft environment must address complex aspects including organ physiological fremitus and blood vessel flow pressure. In [2]**,** a systematic review of recent research on bilateral teleoperation systems in soft settings is presented. A significant transmission latency can cause a master-slave disconnection if the slave's contact force is not immediately detected. The BRL/Pisa/IIT SoftHand, a low-cost, 3D-printed, tendon-driven robot hand, employs soft and adaptable synergies for various gripping tasks [3]. In [4], a comprehensive testbed is presented as a vital step towards establishing infrastructure for 5G systems and Tactile Internet applications. It stresses software-defined networking and network function virtualization for 5G networks and Tactile Internet applications. This survey aims to provide an overall survey and use cases for sensory data transmitted using 5G and B5G networks. The objective of this survey is to focus on challenges for multiple sensor data transmission using 5G and beyond network technologies, as well as how significant is to receive this information without losing them. This article is organized into individual sections where section 2 provides a basic introduction to the importance of multi-modal sensory transmission in the healthcare sector. Section 3 includes significant challenges of multimodal sensory transmission over a 5G network. Some network and transport layer protocols for multi-modal data transmission are mentioned in section 4. Section 5 detailed use cases and comparative studies available and published, and section 6 concluded with the outcome of this survey with future research directions in this field.

2 Motivation and vision

To provide ultra-low latency for a high-quality immersive experience in multi-sensory transmission, this article presented insights into the numerous contributions made by technology breakthroughs in B5G networks. The latency requirements for a teleoperation system include an interactive remote environment that typically spans from 120 ms to 700 ms. This range facilitates the provision of more elaborate visual content, characterized by a higher resolution, frame rate, low packet error rate, and 360° spherical six- degree-of-freedom (DoF) content. While B5G is instrumental in facilitating higher bandwidths than 4G, its capacity to enhance low latency is relatively limited without compromising on bandwidth, robustness, and availability.

The primary objective of this survey is to provide a thorough and cutting-edge proposal aimed at implementing a technology interface that incorporates multi-modal sensory fusion in wireless networks based on B5G/6G and IIoT. The present discourse sheds light on the implementation of 5G networking in healthcare and its essential prerequisites. The survey highlights the significance of 5G technology in multi-sensory transmission, which is crucial for maintaining seamless connectivity of multi-sensory systems without any latency or buffering at the user's end. Multi-modal interactions using visual, sensing, kinetic, and audio inputs are all part of the investigation of multi-modal sensory substitution using 5G networks. According to one study, tactile robotic telesurgery enabled by 5G may be feasible given the need for multimodal sensory data [1]. Although there may not be much information on multi-modal sensory substitution with a 5G network, using this technology could enhance the rate and latency of multi-modal interactions as well as open up novel prospects for applications and services [28]. The advantages of multimodality in VR include increased user engagement, better learning transfer, enhanced performance, and the capacity to duplicate and manipulate real-life circumstances that are difficult or expensive to replicate in conventional training environments [59].

There are currently no specific examples of multi-modal sensory substitution in 5G networks in the literature. Within 5G networks, there is a lot of research into multi-modal interactions that combine inputs from the visual, sensing, kinetic, and auditory modalities. A study suggests that using different cross-modal mappings over several sensory channels may help current sensory substitution devices function more effectively. Another academic study looks at the idea of multimodal inclusive design that uses sensory replacement. The goal is to develop thorough cross-modal exhibits that can successfully transmit the same sensory data over a variety of sensory modalities. Currently, sensory replacement techniques are not widely used in mainstream technologies. However, there is a lot of opportunity for cross-modal devices that use these methods to develop in the future.

This article initially gives a general review of 5G and 6G networks as well as multimodal sensory transmission in this article. We also demonstrated some frequent implementation issues for 5G-enabled multisensorial media transmission. Following that, a broad comparison and case studies were given, covering the commonly utilized haptic devices as well as the current difficulties with teleoperation systems. Additionally, all transport and network layer protocols that, support multi-modal communication have been listed and qualitatively evaluated, with a particular focus on the management and synchronization of haptic, video, and audio data streams. Presenting the most recent developments in 5G and 6G networking infrastructure from the perspective of multisensory transmission was the primary objective of the next section. At the end, we discussed the upcoming difficulties with multi sensor transmission over 5G networks and provided a summary of the lessons discovered from this survey.

3 Related work

Table 1 provides a comprehensive overview of the current literature on multi-modal sensory substitution and the tactile internet, including the integration of intelligent technologies such as machine learning (ML)/deep learning (DL) and augmented/virtual reality (AR/VR) within the wireless cellular communication network in 5G/B5G environments. The possibility of 5G technology for telemonitored surgery is covered in [1], along with technical details, cost/benefit analysis, and safety and efficacy considerations. In Ref. [2] discusses the potential of cellular-supported B5G wireless connectivity in XR-aided teleoperation systems for industrial and piloting use cases with unique quality of service requirements. The current state of the telesurgery robotic system's development has been presented in [3].

AaYusH revolutionizes telesurgery in Healthcare 4.0 by leveraging Ethereum smart contracts and the InterPlanetary File System to enhance security, and privacy, reduce storage costs, and outperform traditional systems in latency and data storage efficiency [6]. A new framework using machine learning and Hidden Markov Models to forecast needle insertion haptic feedback failures during remote robotic surgery [8] could meet 5G latency requirements. In this study [11], 5G telerobotic spinal surgery was tested in twelve different cases and demonstrated promising results in treating spinal issues. In Ref. [17] reviews the novel design of a mobile robot teleoperation system that uses 5G technology to enable seamless and interactive human-robot communication.

Figure 1 illustrates the Prisma graph for the number of relevant papers. According to Fig. 1, it can be seen that most articles are present between the years 2019 to 2023. The latest articles have been also added in the references and according to the Prisma graph, the numbers are based on the keywords search query mentioned in Table 1. Figure 2 displays the connected papers graph based on the number of citations, usually, this showcases the interconnection between relevant papers cited in recent years. The Tactile Internet must taken into account the delivery of audio and visual input in addition to haptic feedback, primarily at the master domain, because the human brain integrates various sensory modalities, resulting in improved perceptual performance [5]. A fundamental difficulty in this context is cross-modal asynchrony, which arises because different modalities (visual, auditory, and haptic) have distinct

Table 1 Keyword query search publications

Keyword	IEEE Xplore	PubMed	ACM Digital	Scopus
Tactile communication OR 5G	330	1011	2675	341
Haptic communication AND 5G	136	13	2674	125
Bilateral teleoperation	863	64	2776	1920
Challenges OR Tactile Internet OR 5G	1823	546,952	1279	2792
Tactile Internet OR B5G	1963	445	22,372	51
Multi-sensory data transmission AND AI-ML	4	11	760	16

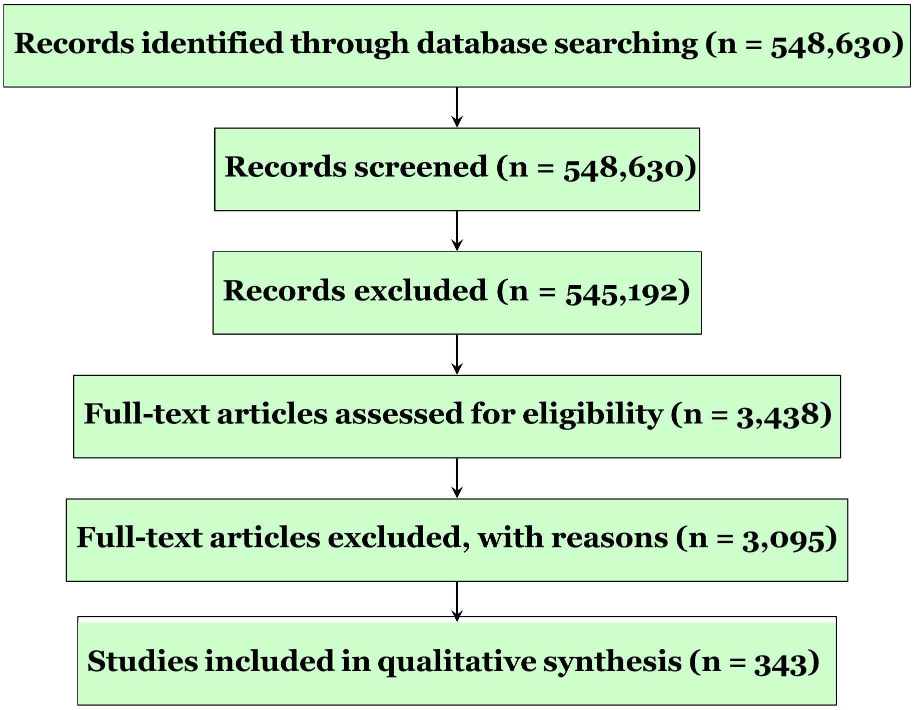


Fig. 1 PRISMA flow diagram for study selection process

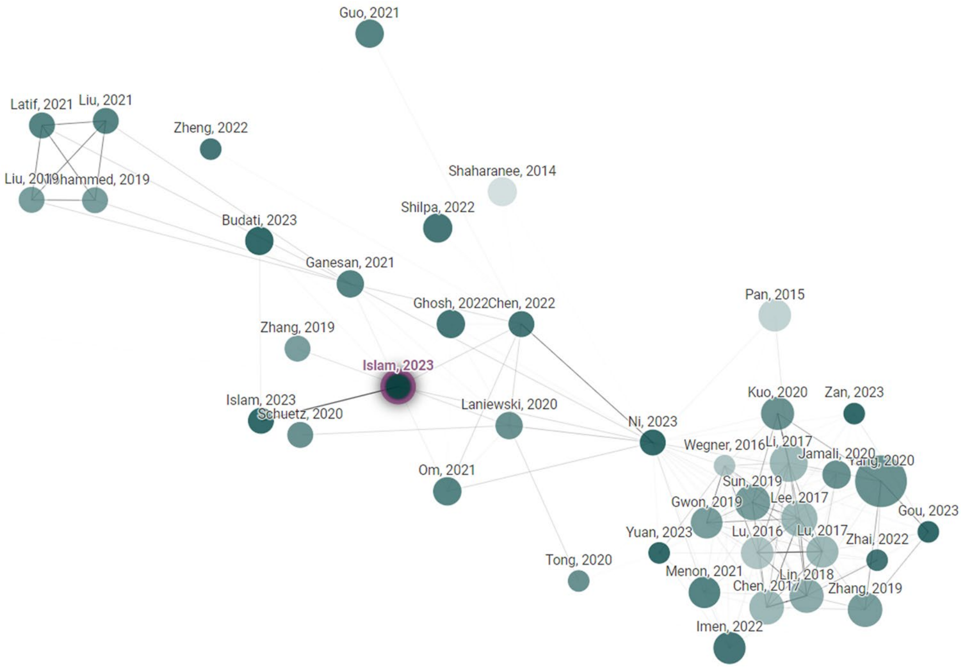


Fig. 2 Literature graph for relevant papers

requirements in terms of sampling, transmission rate, latency, etc [43]. As a result, a multiplexing method that can take advantage of priorities, as well as the temporal integration of many modalities, is needed. Some initial research attempts aim at addressing this difficulty. Similarly, in [51] the authors offer a Learning to be Multimodal as Sensory Modalities and Sensor Properties approach.

The authors of [63] present a wireless-connected virtual reality and haptic communication open platform for multimodal teleoperation systems with a focus on practical implementation and performance evaluation. However, because the master device does not receive signal input from the slave site, the operator cannot intuitively sense how the environment is interacting with the slave manipulator. As a result, the slave object cannot be precisely controlled, especially when interaction force is taken into account [70]. Tactile Internet human-machine haptic interactions require minimal latency [7]. The Tactile Internet needs a 1–10 ms end-to-end delay for haptic applications, especially teleoperation case studies [14]. The Tactile Internet needs ultra-reliable, low-latency connectivity to reduce motion sickness. The Tactile Internet can connect virtual objects to the real world with 1 ms latency and 99.999% reliability [12]. During 2022, Bolarinwa included the teleoperation sensory feedback performance in the doctoral dissertation [27].

Wireless sensor networks can collect manufacturing data to optimize production and product quality [68]. Articles [19] and [22] provide a holistic testbed as a crucial step towards developing an infrastructure for 5G systems and Tactile Internet applications. It also emphasizes the significance of software-defined networking (SDN) and network function virtualization (NFV) for 5G networks and Tactile Internet applications. The utilization of Haptics over Internet Protocol (HoIP) is recommended by authors, which involves the transmission of multimodal data between remote locations using user datagram protocol (UDP) and Internet protocol (IP) [83].

In rural China, a 5G-based robot-assisted remote ultrasonography system was successfully used in a crippled patient care centre [38]. A prospective study on a rural island shows that a 5G-based telerobotic ultrasound system can provide high-quality thyroid assessments and initial disease management in areas with limited medical resources [39]. The study [76] shows that a 5G-based telerobotic ultrasound system can improve breast examinations in rural and isolated places, giving a promising alternative for neglected healthcare. Table 2 demonstrates the gaps present in the published articles and focuses on this survey with its description. Many authors and researchers have written and published manuscripts where a few points are missing and this article covers those points in detail like challenges in multi-sensory transmission and protocols used for haptic feedback and tactile internet.

At last, by this survey, it is clear that communication is a key point parameter for bidirectional telerobotic surgeries which use multi-modal data transmission. This survey includes below mentioned key points:

1. First, we provide a quick overview of multi-sensory data transmission. With a brief description of a multi-media sensory transmission, we intended to demonstrate the comparative survey structure of the importance of networking.
2. We also give some background information on the tactile internet and haptic feedback technology To support the haptic technology interface in the B5G/6G domain, we propose an end-to-end (E2E) latency interfacing architecture with other challenges and issues in implementation.
3. We also provide information on the effects of edge computing and AI/ML technologies on 5G and 6G multimedia data transmission, along with privacy and security measurements. This survey briefly discussed that multi-media transmission involves physical-to-application technology depending on the transport and network layered architecture.
4. We continue to address the research problems and expand our investigation into the implementation of the future generation (6G) and ultra-low latency-based 6G and IoT applications by healthcare in terms of multi-modal sensory substitution.

4 Paper overview

The architecture of this survey is as follows: In section 2 covered the multimodal sensory transmission over a 5G network and its importance in healthcare. Section 3 is concerned with how latency, security and interfacing cost challenges affect the multimodal approach for sensory data transmission. The network layer and transport layer for tactile internet and haptic technology have been demonstrated in section 4. Next, Section 5 includes the comparison of multimodal sensory transmission over the last few years and real-time case studies. Furthermore, section 6 discussed the outcome of this survey and future research direction in tactile internet and telerobotic operation using beyond 5G network. In the final part of this article, Section 7, we draw our conclusions. The layout of the document, as well as its overall structure, may be found in Figure 3 below, where major points are covered within this article.

Table 2 Gaps in literature and proposed solutions for multi-sensory data transmission

Gap in Literature	Description	Focus of paper
Insufficient and thorough studies on multi-sensory data	Existing research lacks a comprehensive understanding of multi-sensory data trans- mission systems	A comparative survey framework high- lighting the significance of networking
Poor investigation of tactile inter- net applications	There is a lack of detailed study on the practical implementation of tactile internet in practical applications	A thorough examination of haptic internet applications using 5G and beyond 5G (B5G) technology
Challenges in latency minimization	Current literature do not adequately ad- dress latency issues in multi-modal sensory transmission	Development of a latency-minimized multimodal approach
The insufficiently investigated im- plications of edge computing	The literature regarding the impact of edge computing on strengthening the transmission of sensory data need to be more comprehensive	Examination of edge computing effects on 5G and 6G multimedia data
Need for privacy and security measures	There is a lack of focus on privacy and security in multi-sensory data transmission	Discussion on privacy and security measurements in the context of 5G
Future research directions in tac- tile internet	Limited insights into future research directions for tactile internet and telerobotic operations	Exploration of future research directions in tactile internet and IoT

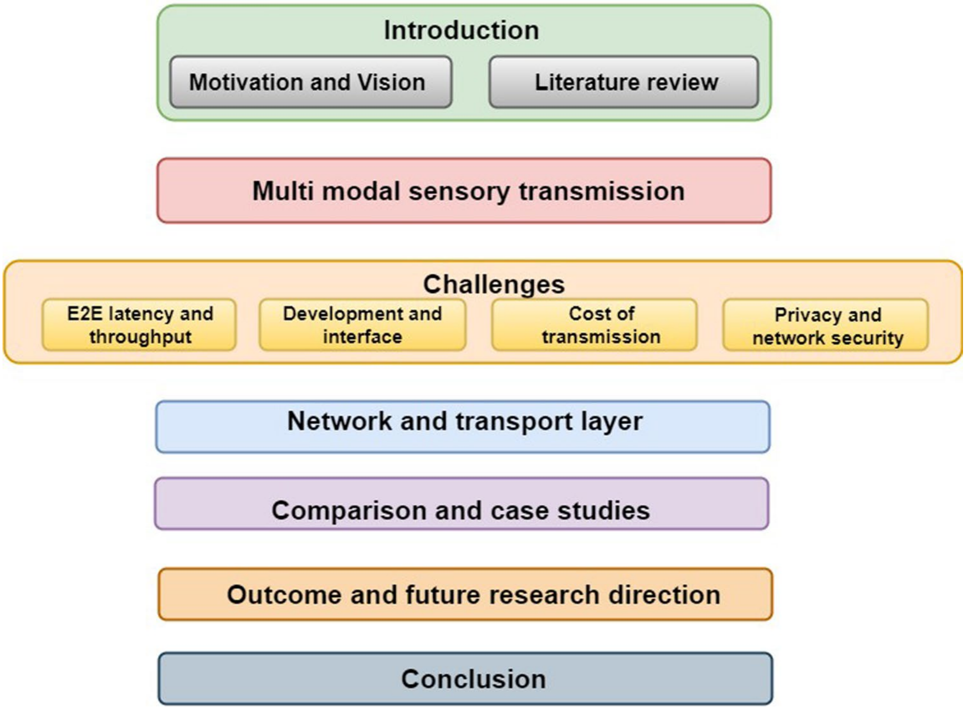


Fig. 3 Overview of the article

5 Multimodal sensory transmission

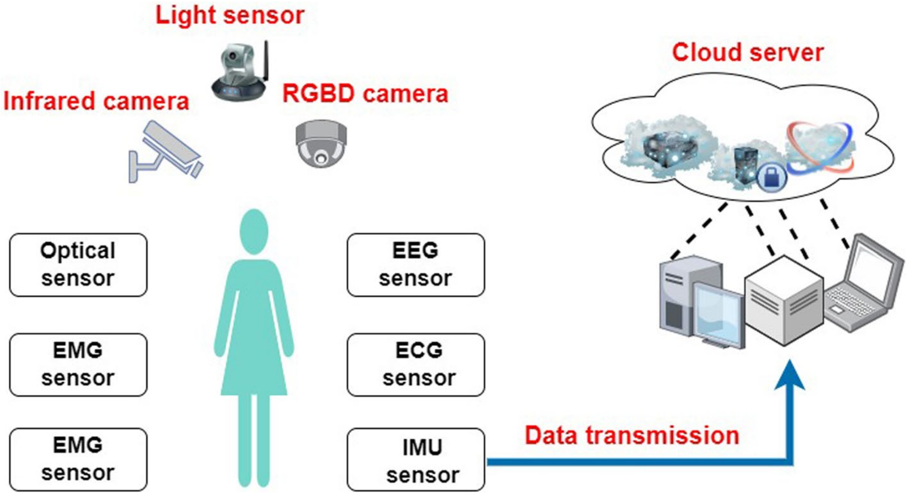
Mulsemedia—multiple sensorial media- wants to make the user experience more immersive and interesting by incorporating other senses like taste, smell, and touch. A more compelling and realistic user experience can result from the integration of several senses in multimodal media, which also increases the sensation of involvement and presence. Mulsemedia is intimately linked to the advancement of technologies that facilitate the delivery of multi-sensory content, such as Holographic-Type Communication (HTC) and Extended Reality (XR). A comprehensive subject study showed that a multimodal feedback system for visually impaired people can improve orientation and movement by providing intuitive and flexible auditory and vibrotactile input [45].

Multimedia, often known as multiple sensorial media, is a category of multimedia that incorporates more than three senses. The attempt to add multisensoriality to multimedia content to give users a more engaging experience gave rise to this field. Here, the media types—their creation, dissemination, and rendering—are the main subjects of interest. On the other hand, the term "multimodal" (multiple modalities) describes how communication and interaction practices employ many semiotic modes, such as verbal (speaking, text, etc.), nonverbal (facial expressions, gesture, eye gazing, etc.), and contextual modes. Here, the modality and the interpretation of data to transmit meaning are the main points of interest. A novel multimodal sensory apparatus using optoelectronic pressure transducers and IMU technology improves robotic prosthetic foot control and functionality [46].

Multimodal sensory transmission, which includes the integration of different sensory modalities like vision, auditory, touch, taste, and smell, is a crucial part of human perception and interaction with the environment [52–54]. People build a thorough grasp of the world around them by combining several modalities, which makes experiences richer and more complex. Perception of multisensory stimuli—where data from various senses converges and interacts to build a coherent perceptual representation—is made possible by this integration [25, 56]. A deeper and more comprehensive understanding of the human experience is made possible by the synergy between various sensory inputs, which enhances processing accuracy and efficiency in both simple and complicated cognitive activities [55].

The investigation of multimodal sensory transmission has recently expanded into technology develop- ment and human-computer interaction, moving beyond the domain of human perception. Engineers and researchers have been working hard to duplicate multimodal sensory integration and use its power in a variety of applications. As experimental platforms, testbeds have been essential to this effort because they offer settings for the study and optimization of multisensory information transmission and integration which is also displayed in Fig. 4. In order to handle

Fig. 4 Mixed reality



and synchronize sensory input in real time, these testbeds frequently combine sophisticated sensing technologies—such as microphones, cameras, tactile sensors [60], and smell sensors—with computer algorithms. These testbeds allow researchers to investigate the possibilities of multimodal sensory transmission in fields such as virtual reality, augmented reality, healthcare [40], and assistive technology by replicating multisensory settings and interactions.

As earlier mentioned, in bilateral teleoperation, multi-modal sensory integration employs a variety of sensory feedback to give the user a more intuitive and natural teleoperation experience. A multimodal user interface that combines gesture-based teleoperation of the robot [44] with visual and tactile input to the user is used for distant object investigation with scarce sensory data. The user interface includes cutaneous distance perception through vibrotactile actuators integrated with a virtual reality glove [67], surface reconstruction of the remote environment integrating data sampled by tactile and proximity sensors [24], and an optional video information stream for bandwidth-rich settings.

A low-dimensional teleoperation subspace is suggested as a bridge for mapping between hand pose spaces in the teleoperation of non-anthropomorphic hands [57]. The subspace can be defined algorithmically, which is kinematically independent, and empirically, which requires a person to define hand motions in an intuitive, hand-specific manner. The teleoperation subspace may generalize to nonanthropomorphic hands with varied kinematics and is applicable to teleoperation. It is also simple enough for beginners to use. Real-time (task-dependent) positioning of a video camera, which is often attached to the flying base, becomes another goal to be achieved in the teleoperation of a robotic manipulator attached to a flying base. A graphical summary of the various sensory transmissions over the cloud server is shown in Fig. 4. It becomes necessary to manipulate the base position in the null space. In order to give the operator useful details about the restrictions on the permitted motions in the null space.

Multi-sensory teleoperation systems need a communication line with a wide bandwidth for video and audio transmission systems and a short, stable response time for the communication line for haptics transmission systems to be realized. These systems give the operator simultaneous access to auditory, visual, and haptic information from a remote site. This is because since the haptic transmission controller incorporates the delay into its closed control loop, the possible bandwidth of haptic sensation is constrained by the communication line's round-trip time. In reality, a human can detect touch at the tip of a finger up to 400 Hz

A 5G network could be used to improve a multimodal user interface for remote object investigation with low sensory input by offering high-speed video streaming. The user interface combines visual data with information gathered by video sensors, vibrotactile actuators built into a virtual reality glove, and data collected by touch and proximity sensors. High-quality video streaming could be made possible by a 5G network, giving the user a more natural and intuitive experience when operating a remote robot. The necessary bandwidth for the transmission of high-quality video and audio may be available over a 5G network. A haptic transmission system, however, needs a communication channel with a short and consistent delay performance. In actuality, a human can detect touch at the tip of a finger up to 400 Hz.

The high need for haptic input is the primary source of challenges and limitations associated with the implementation of multi-modal sensory substitution using a 5G network for teleoperation [71]. According to [80], there are several network related challenges also taken care of while designing 5G enabled teleoperation. Based on Shannon's sampling theory, a haptics transmission system needs to have a short and steady performance of delay for the communication

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line, as well as a round trip time of the communication line that is less than 1 millisecond. This is necessary to recognize the bandwidth of haptic sensation. This amount is significantly lower than the maximum delay that audio and video transmission systems, which necessitate a large bandwidth for the communication connection, are permitted to have. Therefore, it is possible that a 5G network will not be adequate for providing haptic feedback in teleoperation.

5.1 Importance of multi-sensory data transmission using 5G and B5G-enabled networks in healthcare systems

By integrating of multi-sensory data transmission using 5G and B5G-enabled networks in healthcare systems, medical services improved and became fast with low-delay communication. These technologies facilitate the smooth connection of medical devices, allowing for immediate monitoring and remote diagnosis by delivering a significant amount of varied sensory data, including physiological measurements, high-definition photos and videos. This feature enables the use of sophisticated applications as mentioned earlier AR/VR, robotic telesurgeries and so on. Furthermore, the implementation of artificial intelligence and edge computing in conjunction with 5G networks improves the processing and analysis of data.

- Enhanced patient monitoring: Low latency and high bandwidth offered by 5G and B5G networks allow for real-time patient monitoring using a variety of sensors. For patients with chronic diseases in particular, this is essential for ongoing health monitoring. Numerous wearable health devices that monitor vital signs including blood pressure, heart rate, glucose levels, and more are supported by these networks, which send data to healthcare providers continuously.
- Data management and analysis: Big data approaches can be used to analyze the massive amounts of data generated by multi-sensory devices to identify patterns, predict pandemics, and improve the health of patients.
- Remote and home care services: Elderly people can benefit from remote monitoring and care through multi-sensory data transmission, which enables them to remain in their homes for longer periods while still getting the necessary medical treatment.
- Smart things: "Smart things," sometimes known as "smart devices," are a broad category of networked devices that make use of cutting-edge technologies to improve functionality, convenience, and efficiency in a variety of everyday situations.

6 Challenges of multimodal sensory transmission over 5G network

Integrating multimodal sensory transmission into 5G networks presents various challenges, such as minimis- ing latency, maintaining storage capacity, and keeping a consistent quality of service. To overcome these problems, ensuring interoperability between hardware platforms, achieving efficient software integration, and establishing seamless interfaces for different sensory inputs is imperative. Furthermore, the complexity is increased by the necessity for maintaining robust privacy and security protocols throughout data transfer, as well as the real-time synchronization and organization of data streams. Among them, a few challenges have been thoroughly discussed below:

6.1 E2E latency and throughput

The challenges related to transmitting multimodal sensory data via 5G networks are greatly impacted by the latency and throughput of the End-to-End (E2E) communication. E2E latency refers to the overall delay experienced when transmitting data from the source to the destination, which in turn affects the real-time transfer of data. On the other hand, throughput refers to the quantity of data that can be transmitted over a certain time.

Thus, an important question arises regarding the amount of delay about the amount of data loss that a system can tolerate. According to a study conducted by Eckehard Steinbach in [16], it has been proven that a significant decrease of 90% can be obtained. The end-to-end latency for transmitting multiple sensory inputs across 5G networks is affected by various factors, such as network structure, deployment circumstances, and caching strategies. However, applications that demand minimal delay in 5G networks require a total delay that can vary between 1 ms and 100 ms. The technical challenges of 5G networks involve achieving extremely low latency and minimizing circuit complexity. In 2020, Alperen Acemoglu et al. published the results of 5G enabled telesurgery using Franka Emika robot and Omega haptic device and concluded the round trip time between 124 ms to 170 ms [37].

The E2E latency in 5G networks is influenced by the placement of Access Servers (ASs), the implementation of Mobile/Multi-Access Edge Computing (MEC) nodes, the interconnection points between networks, the configuration of the radio access network, and the installation of the core network. Research indicates that the end-to-end (E2E) latency values for 5G Vehicle-to-Everything (V2X) services can range from 17.8 ms for deployments based on Multi-access Edge Computing (MEC) to 53.8 ms when Access Servers (ASs) are located in central clouds that can be accessed online. Attaining a low end-to-end (E2E) latency is crucial for applications like connected ambulances, where the required latency ranges from around 250 ms for transmitting vital signs to approximately 10 ms for delivering haptic feedback. Table 3 displays a comparative examination of latencies associated with 5G and B5G. The investigation covers latencies for many applications, including robotic telesurgeries and human-robot interactions. The table additionally incorporates data obtained from an experimental configuration.

The throughput requirements vary significantly depending on the characteristics of the data being delivered. For instance, the required data rate ranges from 10 Kbps for transmitting vital signs to 1.6 Gbps for streaming 3D cameras in healthcare applications across 5G networks. Ensuring sufficient throughput is essential for the continuous transmission of high-definition video, audio, and other multi-modal sensor data, without any interruptions or delays.

The throughput of multi-modal sensory transmission across 5G networks significantly affects the quality of data transfer. Increased throughput enables the transmission of larger quantities of data, including high-definition audio and video as well as other sensor data, resulting in improved accuracy and perfection in the transmitted information. Increased throughput in 5G networks enhances the dependability of transmitting multimodal sensor data by reducing the probability of packet loss or delays that could compromise the quality and integrity of the data. Lower latency resulting from higher throughput increases the adaptability and utility of multimodal sensory transmission, resulting in improved user

experience and overall data quality. The higher throughput capacity of 5G networks offers an extensive and accurate representation of multimodal sensory data. This is achieved by enabling the simultaneous transfer of multiple types of data from numerous sensors.

6.2 Development and interfacing

The implementation of multi-sensory transmission over 5G networks presents significant challenges which require addressing several technical issues [85]. To protect the network from potential security and privacy issues, it is crucial to implement technical controls, construct a robust network structure, and rigorously evaluate the placement of devices. The subject of attention is buffer management. Challenges encountered by 5G cellular networks involve the incorporation of efficient data traffic management that guarantees minimal delay and decreases the complex nature of circuits. Optimizing the distribution of equipment is essential for successfully controlling delays and accommodating the increasing data rate traffic, hence increasing the overall user experience. The complex nature of transmitting many sensory inputs via 5G networks requires complicated network architectures, resulting in intensive computational operations and the requirement for large amounts of data for learning [78].

The integration and processing of data from several multimodal sensors, such as video, audio, and haptic, requires an innovative computational approach. The computational challenges presented by multimodal data are significant due to its different forms and the need to effectively arrange, combine, and evaluate it. The large quantity of multimodal sensor data generated in 5G networks requires the implementation of robust data storage technologies that can efficiently handle this huge data volume. A major challenge consists in the effective storage and administration of diverse multimodal data, prioritizing the guarantee of quick accessibility and processing.

A significant challenge is the absence of comprehensive information systems and platforms that effectively manage the expansion and integration of multimodal sensory transmission. The lack of standardized protocols and guidelines for transmitting multimodal data might slow the advancement and easy integration of various systems and devices. To ensure uninterrupted development and smooth implementation of multimodal sensory transmission across 5G networks, it is crucial to establish uniform frameworks and standards. Mantisha Gupta and her colleagues conducted a study on tactile-based intelligence using Touch Technology in B5G/6G IoT Configured WCN. This research is referenced as [91]. An observation suggests that the incorporation of touch-enabled sensation and actuation has the potential to change wireless communication networks. Their work focuses on uninterrupted connection and the evolution of wireless communication from 1G to 5G, with plans for 6G networks by 2030 [91].

Table 3 Latency comparison table

Latency	Article	5G or B5G	Experimental or survey	TI present or absent	Application
102 ± 9 ms	[4]	5G (URLLC)	Experimental	Absent	Robotic Telesurgery: Remote Transoral Laser Microsurgeries
Range 1–2 ms and 4–6 ms	[7]	5G(URLLC)	Experimental	Present	Tactile Internet Services
RTT of 5 ms and 2 ms for shorter links	[9]	NA	Experimental	Absent	QoS prioritization or router bypassing
0, 350, 700 ms	[10]	NA	Experimental	Absent	Telesurgery
< 1 ms	[14]	5G(URLLC)	Survey	Present	Tactile-Internet-Based Telesurgery System
500, 750, 1000 µs	[20]	5G(URLLC)	Experimental	Present	PHY/MAC Design for Printing Machine
1 ms to 10 ms	[21]	5G (URLLC)	Experimental	Absent	Radio Network Design
100–700 ms (Warm-up), 1000 ms (Test)	[23]	5G (URLLC)	Experimental	Absent	Human–Robot Collaborations
maximum latency of 1 ms	[42]	5G(URLLC)	Survey	Present	Tactile internet and Internet of Things in context with 5G rev- olution
239 ms—319 ms	[73]	5G	Experimental	Absent	Teleoperation of an Industrial Robot using Public Networks
88 ms (or 10 ms in case of a 54 Mbps network)	[79]	NA	Experimental	Absent	ROS communication protocols
5–6 ms for time-sensitive AR/VR applications	[81]	5G(URLLC)	Survey	Present	Augmented and Virtual Reality
Two-way latency of 27.5 ms with VH-multiplexer versus 17.2 ms with ViTaLS for N = 7	[89]	NA	Experimental	Present	The video-tactile frame transmissions

6.3 Cost of data transmission

The transmission of multiple sensory inputs in teleoperation systems necessitates the communication of a substantial number of data packets per second between the master and slave devices. The transmission of audio and video data, in conjunction with a high packet rate, can result in the utilization of significant network resources, leading to inefficient data transfer. Hence, it is essential to include sensory data reduction, also known as packet rate reduction, within teleoperation systems [78]. In addition, the processing of tactile information, particularly when dealing with complex textured surfaces, necessitates the utilization of data reduction techniques.

The metaverse necessitates the utilization of data rates that are exceptionally high, dependability that is exceptionally high, and communications with latency that is exceptionally low, all while possessing compute capabilities in both core and edge networks [93]. The expenses associated with constructing the foundational infrastructure for the 5G network are very high, rendering it financially impractical. Moreover, the inclusion of supplementary base stations necessary for ensuring dependable connectivity further amplifies the overall expenses and intricacy of the network. The objective of the suggested technique is to address the aforementioned issue by utilizing sustainable and robust 5G energy signals for remote operations, hence enabling multi-sensory real-time data transmission. The approach employs sustainable and resilient 5G energy signals to transmit multi-sensory data in real-time, hence resulting in a reduction in the expenses associated with data transmission [85].

The products that are already on the market could not be compatible with 5G infrastructure, which would need customers to upgrade their gadgets to take use of the multimodal sensory transmission capabilities. A major obstacle to gaining wide credibility could be the cost of 5G-compatible devices, especially in the initial phases of deployment. Significant energy consumption may arise from the transmission of large volumes of multimodal sensor data via 5G networks, which would raise power costs and operating expenses [68].

The maintenance of sustainability and cost-effectiveness in 5G-enabled applications necessitates the prioritization of energy-efficient multimodal data transmission. The process of acquiring and licensing spectrum. The acquisition of spectrum for 5G networks necessitates substantial financial investments, as wireless carriers are required to pay considerable sums for the high-frequency bands, which extend up to 300 GHz. The charges associated with spectrum licensing and management can contribute to the overall costs of implementing 5G networks to facilitate the transmission of multimodal sensory data.

Maintenance and operational expenses can be greater for 5G networks due to their increasing complexity, which includes the addition of more base stations and the utilization of new technology, in comparison to earlier generations of cellular networks. Ensuring the dependable and effective functioning of 5G networks

to facilitate the transmission of multimodal sensory data can incur substantial recurring costs.

6.4 Privacy and network security

The wireless element of AR/VR network design creates challenges regarding the reliability of traffic behaviour for information or video frames. The main source of this is short-term disruptions produced by impairments in the signal-to-interference-plus-noise ratio (SINR). However, increasing reliability always results in higher latency since repaired frames need to be re-transmitted at the physical layer using parity, which causes additional delay. To achieve a smooth and engaging augmented reality/virtual reality (AR/VR) experience in the context of 5G technology, it is crucial to have a highly dependable tracking message signaling with a maximum packet error rate (PER) of 10^{-5}. Hence, it is important that these packets are transferred with a high level of dependability to ensure a flawless virtual reality (VR) service.

To meet the mentioned requirements, it is necessary to create a schedule optimization framework that effectively balances the conflicting needs of minimal delay and maximum dependability within the context of immersive virtual reality (VR). This framework should especially address scenarios in which frame delivery breaks. The proactive computing and caching technique generates high-definition frames that correlate to the user’s anticipated movement and head rotation. This technique uses multiple priority levels for real-time processing.

The implementation of multimodal sensory transmission across a 5G network presents several challenges, with security being the primary concern [85]. Despite the enhanced capabilities of 5G, there are independent challenges that need to be addressed. The transmission of sensitive information from multiple sensors over a wireless network gives rise to concerns regarding the security of the network. Ensuring that the confidentiality and integrity of multimodal data is crucial to prevent unauthorized access and breaches. An investigation has been conducted to address the issues related to security, dependability, and performance. This investigation used a consistent classification framework, as described in [61]. Below are several potential security threats associated with multimodal sensory transmission over 5G networks:

- Eavesdropping and Interception: The high bandwidth and low latency of 5G networks may make it easier for attackers to intercept and eavesdrop on multimodal sensor data transmissions, hence creating a risk to user privacy and data integrity.
- DoS (denial-of-service) attacks: Multimodal sensory data transmission may become unavailable in 5G-enabled IoT scenarios due to the vast number of connected devices and high data rates that can expose the network to Distributed Denial of Service (DDoS) attacks.
- Location Tracking: There are serious privacy dangers associated with attackers being able to track user movements and activities using the precise location data that multimodal sensors in 5G networks transmit.
- Malware and Unauthorized Access: Malware can penetrate insecure IoT devices linked to 5G networks, giving attackers access to the multimodal sensor data without authorization and the ability to take control of the devices.
- Signalling Attacks: Attackers may use flaws in 5G signalling protocols, like the GTP (GPRS Tunneling Protocol), to create signalling-based attacks that obstruct the transfer of multimodal sensor data.
- Jamming and Interference: Especially in crucial applications, adversaries may try to jam or interfere with the high frequency 5G signals, preventing the trustworthy transfer of multimodal sensor data.
- Insider Threats: The availability, security, and integrity of multimodal sensor data streams are vulnerable to compromise by negative insiders with access to 5G network infrastructure or IoT devices.
- Lack of Standardization and Interoperability: Vulnerabilities and interoperability problems can result in 5G networks' multimodal data transfer being subject to attacks due to the lack of unified security standards and protocols.

7 Network and transport layer protocols for multi-modal data transmission

Multi-connection refers to the capability of a system or device to make many connections. The Multi-Transport Internet Protocol (MTIP) is a communication protocol specifically developed for enabling real-time haptic feedback and tactile interactions over the Internet. The Multi-Transport Internet Protocol (MTIP) is a transport layer protocol that uses multiple connections with knowledge of the context around them to achieve lower latency and improved dependability by making use of the available communication technologies. The MTIP system leverages application and network status data to automatically establish network paths, hence improving both reliability and latency.

Multipath TCP (MPTCP) is a transport layer protocol that enables the efficient use of multiple routes for data transmission. Implementing Multipath TCP (MPTCP) has the capability to improve both the reliability and bandwidth of Tactile Internet connections. This is accomplished by utilizing many pathways for the transfer of data. QUIC, or Quick UDP Internet Connections, is a transport layer protocol that utilizes UDP (User Datagram Protocol) instead of TCP (Transmission Control Protocol) to improve the performance of web applications.

QUIC may significantly optimize the performance of Tactile Internet apps by reducing latency and enhancing reliability. MPQUIC, an abbreviation for Multipath Quick UDP Internet Connections, is a protocol that facilitates the transmission of data over several paths in the context of UDP. The MPQUIC protocol, also referred to as QUIC, is a transport layer protocol that combines the benefits of MPTCP and QUIC to enable the use of multiple paths for transferring data over UDP. MPQUIC has the potential to improve the reliability and speed of Tactile Internet connections by using multiple transmission pathways.

The Multipath Real-time Transport Protocol (MPRTP) is a transport layer protocol specifically developed to enable the effective transmission of real-time data by utilizing multiple routes. Implementing the Multi-Path Reliable Transport Protocol (MPRTP) can improve the reliability and speed of Tactile Internet connections by using multiple transmission paths for real-time data.

The Haptic Communication Protocol (HCP) is a dedicated protocol designed primarily to enable the instantaneous transfer of haptic information. The main focus is on transmitting data related to tactile and haptic feedback. The Border Gateway Protocol (BGP) is a well-established external gateway protocol that enables the exchange of routing and reachability information [66]. Its important responsibility is to ensure the existence of reliable and duplicated routes inside the network.

The Adaptive Multimedia Delivery Solution (ADAMS) is a framework that uses a client-server architecture to regulate data rates for different multimedia streams based on human perception limits. The MPEG Media Transport is an application layer transport protocol that addresses the limitations of RTP. It is mainly used for transferring multi-modal data in 3D tele-immersion environments (3DTI). A proposed approach has been introduced for transmitting video and haptic data in physical teleoperation systems that use constant bitrate communication channels. This approach incorporates the use of perceptual data reduction through the Zero-Order Hold (ZOH) method.

During the process of multiplexing, video data is prioritized when there is no force data to be transferred. Accurate demultiplexing of the data stream can be performed by assuming a connection with a constant bitrate, which involves computing the packet delay and utilising it accordingly. The Haptics over Internet Protocol (HoIP) framework, which will be analyzed in later sections of this paper, also employs the Just Noticeable Difference (JND) technique. HoIP, developed in C++, uses the unstable User Datagram Protocol (UDP) together with a multiplexing technique. This method enables the division of either haptic and audio data or haptic and video data into packets.

Constrained Application Protocol, or CoAP, is a network layer protocol suitable for Internet of Things applications involving the transport of many multi-sensory data types. It provides machine-to-machine (M2M) communications using a lightweight alternative to HTTP and is designed to work with constrained networks and devices. Internet of Things (IoT)-specific protocols like Sigfox, LoRaWAN, and MQTT are normalized by CoAP onto the AMQP 1.0 protocol, which is frequently utilized in storage facilities and can handle demands for throughput and backpressure. Consequently, CoAP may handle an array of IoT protocols and enable interoperability between different IoT devices and cloud applications.

Advanced Message Queuing Protocol, or AMQP, is a network layer protocol that makes it easier for devices to send multimodal data reliably and efficiently. Message-oriented middleware, which allows different applications and systems to exchange different types of information, is made possible by this open standard application layer protocol. Among the many benefits of AMQP for the Internet of Things and other distributed systems that require reliable and secure data transmission are message queuing, routing, security, and reliability. AMQP is widely used as the communications backbone for IoT systems and frameworks because Eclipse Hono normalizes several IoT protocols onto the AMQP 1.0 protocol.

CoAP processes multi-sensory data with minimal overhead, which makes it suitable for Internet of Things devices with constrained power and memory [72]. Sending a single request to numerous devices using multicast communication in CoAP is helpful for managing numerous sensors or actuators. Easy translation to HTTP for online integration and effective multi-sensory data transfer is made possible by CoAP's ease of use and HTTP integration. CoAP is connected to UDP by default and optionally to DTLS (Datagram Transport Layer Security) for dependable and safe multi-sensory data transfer. CoAP is designed to function smoothly on microcontrollers with limited resources, requiring as little as 10 KiB of RAM and 100 KiB of code space. This optimization allows low-power devices to consume less energy while CoAP effectively manages data flow.

Below is a summary of the main transport layer protocols used for transmitting multi-sensory data. These transport layer protocols provide several ways to address the problems of dependable, effective, and immediate transmission of multi-sensory data across a range of applications and network contexts. Each protocol has its own special capabilities and design considerations:

(a) Stream Control Transmission Protocol (SCTP): SCTP is a transport layer connection layer protocol that is reliable and sequential in its data transmission operations. Data can be split up into multiple streams inside a single association due to its multi-streaming capabilities. Multiple IP addresses can be assigned to an endpoint due to SCTP's multi-homing feature, which provides redundancy and fallback possibilities. These qualities make SCTP a great option for reliably and efficiently sending a range of multi-sensory data kinds, such as audio, video, and haptic feedback.
(b) Internet Reliable Transaction Protocol (IRTP): IRTP is a transport layer protocol that can be used to frequently transfer transaction-oriented data, such as control signals and sensor measurements. Its characteristics, including guaranteed delivery, duplicate detection, and transaction-level flow management, make it suitable for multi-sensory data transfer in industrial and Internet of Things applications. The reliable and precise distribution of multi-sensory data becomes possible by the IRTP's dependability mechanisms and transaction-oriented architecture.
(c) Sensor Transmission over Reliable and Ordered Network (STRON): In wireless sensor networks, the timely and effective delivery of sensor data is guaranteed by the transport layer protocol called STRON. It includes strategies for handling out-of-order delivery, packet loss, and congestion to ensure dependable and fast multimodal data transfer

from distributed sensor nodes. For multi- sensory applications requiring data transfer from multiple sensor types, STRON is a great option because it has been designed to meet the requirements of sensor networks.

(d) Real-Time Network Protocol (RTNP): The primary objective of the transport layer protocol RTNP is real-time data transfer, which includes streaming media and control signals. It provides features like limited latency, jitter management, and support for several data streams, which make it possible to effectively transmit time-sensitive multisensory data. Applications requiring synchronous and low-latency transmission of a range of sensor data could benefit from RTNP's quality of service (QoS) procedures since it emphasizes real-time [86].

(e) Hierarchical Multicast Transport Protocol (HMTP): An effective multicast data delivery method may involve using the transport layer protocol HMTP when transmitting the same multisensory data to multiple recipients at once. By including techniques like dynamic group management, congestion control, and reliable information delivery, it guarantees the scalable and dependable transmission of multi-sensory data in multicast situations.

(f) Reliable Multicast Transport Protocol (RMTP): RMTP is a transport layer protocol designed to address the problems of packet loss and out-of-order receipt. It provides reliable and sequential transfer of data across many channels. Due to its properties such as receiver-based flow management and selective retransmission, it is capable of transmitting multi-sensory data to multiple destinations while assuring data consistency and integrity.

8 Comparison and case studies

The session included a comprehensive comparison and analysis of commonly used haptic devices, as well as an examination of the current difficulties faced by multi-sensory data transmission teleoperation systems. A thorough analysis has been conducted to evaluate the qualitative aspects of 5G and 6G network technologies and techniques which enable multi-modal communication. The evaluation concentrates specifically on the management and integration of haptic, video, and audio data streams, as referenced in [15]. In [58], Thomas Hulin et al from Germany introduced new approach of model-augmented haptic telemanipulation (MATM) which provides to enable operator assistance efficiently.

Table 4 presents broad information about various robots, such as KUKA, Franka Emika, UMI, and several others. These robots are utilized for different purposes and demonstrate various degrees of freedom. Although other independently designed robots are used in various scenarios such as smart homes, smart hospitals, and other applications, KUKA robots are primarily utilized for industrial purposes. The comparison between the tactile internet over 5G and B5G networks is presented in Tables 5 and 6. These tables include details about the 5G technology name and indicate whether haptic feedback is used.

Table 7 presents a collection of case studies that demonstrate the positive effects of transmitting multi- sensory data through 5G and B5G networks on healthcare systems around the world. The implementation of these technological advancements has contributed to expanded remote diagnostics, telemedicine, and real-time patient monitoring, resulting in an essential growth in healthcare delivery.

8.1 Haptic and tactile data transmission over 5G enabled network

The human somatosensory system controls both the tactile and kinesthetic senses, which are involved in haptic perception. Kinesthetic information helps in the sensation of joint positions and muscle contractions. Pain, warmth, pressure, and touch are examples of tactile information. Almost all neuromuscular processes depend on it [62], including material identification, object perception and location in low light, and other surface properties. A visual representation of the tactile internet is shown in Figure 5, which also highlights the use of numerous multimedia sensors in bilateral teleoperation. It provides complete modules for each individual device and each component of hardware that can be used, as well as a visual representation of the overall architecture.

Haptic applications are significantly affected by network disorders such as packet loss, jitter, network delay, and out-of-order packet delivery, just like other real-time multimedia streaming applications. To accomplish this objective, haptic communication requires both the ability to resist packet loss and the timely delivery of data. Furthermore, it has been observed that fundamental faults in haptic applications may lead to instability in specific situations [26]. This instability is usually caused by a phenomenon known as Packet Delay Variation (PDV), or jitter. The duration of time needed for a packet to go from one node or endpoint to another across a network is descriptive of the latency of the network. Less than 50 ms for the maximum delay, 10 ms for the jitter, and 10% for the packet loss is the ideal range. Delays and jitters

Table 4 Comparative analysis of each robot in relation to its intended use in various applications

Sr no	Year and author	Robot name	DOF	Purpose
1	Abdeldjallil Naceri et al. 2022	Franka Emika robotic system	7	Safe Remote Diagnostics
2	Shengxin Jia et al. 2021	Barrett Whole Arm Manipulator (WAM)	7	Tactile exploration
3	Andre Coelho et al. 2019	Novint Falcon haptic devices	3	telemanipulation experiments
4	C. Pacchierotti et al. 2015	KUKA KR3 manipulator	6	sensory subtraction
5	Domenico Buongiorno et al. 2019	Rehab-Exos (Robotic exoskeleton)	4	home-based telerehabilitation and rescue operations
6	Marco Laghi et al. 2021	Franka Emika end effector Robot System	7	reduce the obstruction of the range of the user's wrist
7	Liqiang Fan et al. 2022	The cable robot model	6	Multimodal haptic interface
8	Davide Simonetti et al. 2016	Kuka LWR-III	7	Neurology and medicine and rehabilitation
9	Amir Yazdani et al. 2022	KUKA follower robot	–	Multi-Sensory Posture Estimation [65]
10	Preet P Modi et al. 2022	UFACTORY xArm5	5	Upper Limb Telerehabilitation
11	Yutao Chen et al. 2023	UR10 manipulator	6	hybrid teleoperation control strategy
12	Magdi Mohsen et al. 2022	JUPITER XL SCARA robot	2	position tracking
13	Abdeldjallil Naceri et al. 2022	Franka Emika robotic arm Leader	7	Tactile Robotic Telemedicine
14	Viviana Moya et al. 2023	NAO robot	–	Delayed and controlled operation
15	Murilo M. Marinho et al. 2023	UMIRobot	5 + 1	Educational kit and the course structure

Table 5 Comparison of Tactile Internet over 5G and B5G network

	Article and year	Tactile internet applications mentioned	Survey or practical implementation	5G or B5G	Haptic feedback used or not	Name of 5G technology
1	[7] (2019)	Industrial applications in hazardous environments, remote telesurgery, intelligent transport system	Survey	5G	Yes	5G new radio
2	[13] (2018)	Telesurgery Robot	Survey	5G	Yes	Edge-Cloud Integration, network Slice, and intelligent edge cloud
3	[16] (2018)	Teleoperation	Survey	5G	Yes	Software Defined Networking (SDN), Network Function Virtualization (NFV), Mobile Edge Computing (MEC)
4	[18] (2016)	Remote surgery, telepresence, Gaming, and virtual reality	Survey	5G	Yes	Cloud-RAN, cloud edge, Mobile edge
5	[19] (2019)	Softwarization and Network Coding	Holistic testbed	5G	No	Software Defined Networking (SDN), Network Function Virtualization (NFV), Mobile Edge Computing (MEC)
6	[20] (2019)	Factory automation, Education, Gaming, Healthcare	Survey	5G	No	NR and LTE technologies
7	[22] (2020)	Telerobotic surgery	Experimental Setup	5G	Yes	eNodeB, LTE
8	[32] (2020)	Telesurgery, vehicle fleets, augmented reality and industrial process automation	Survey	5G	Yes	Software Defined Networking (SDN), Network Function Virtualization (NFV), Mobile Edge Computing (MEC)
9	[36] (2022)	General	Survey	5G	Yes	NA
10	[4] (2021)	Intelligent Stretch Reduction in Information-Centric Networking	Experimental Setup	5G	No	information-centric networking (ICN)
11	[41] (2021)	Smart Manufacturing, Industry 4.0, Society 5.0	Survey	5G	Yes	Network slicing, mmWave, Mobile edge cloud, LTE
12	[42] (2019)	Healthcare 4.0, Industry 4.0, IoT	Survey	5G	Yes	mMIMO, NOMA, URLLC

Table 6 Comparison of Tactile Internet over 5G and B5G network

	Article and year	Tactile internet applications mentioned	Survey or practical implementation	5G or B5G	Haptic feedback used or not	Name of 5G technology
13	[69] (2022)	Industrial Applications	Survey	5G	Yes	Edge Computing
14	[82] (2017)	Haptic communication	Survey	5G	Yes	Network slicing, virtualized network functions (VNFs), radio resource Allocation scheme, coordinated multi-point (CoMP)
15	[83] (2020)	A Teleoperation Case Study	Case study	5G	Yes	NR, mmWave, haptics over Internet protocol (HoIP), Edge A and B
16	[87] (2020)	Industrial automation, Industrial Internet of Things (IIoT)	Testbed	5G	No	NFVI, virtual infrastructure manager (VIM), VNF manager, and the NFV orchestrator (NFVO), Virtualized IIoT gateway
17	[88] (2020)	IoT, haptic communications, Augmented reality (AR), virtual Reality (VR), ultra-reliable and Low-latency communications (URLLC)	Survey	B5G	Yes	Block chain, Edge/Fog computing, SDN based design
18	[90] (2022)	Experimental setup for optical Link performance, commercial IP Television (IPTV) transmission, And the measured result of file Upload/down test	Testbed	B5G	No	time-division multiplexed passive optical networks (TDM-PONs)

Table 7 Case studies of Multi-sensory data transmission using 5G and B5G-enabled networks have empowered healthcare systems

Case Study	Location and Year	Impact	5G or B5G	Details
Remote surgery	China (2020)	Increased availability of high-quality surgical care in remote regions, reducing the need and risks of patient travel	5G	A patient almost 3,000 km away was operated on remotely by Beijing surgeons
Real-time Health Monitoring	US (2021)	Monitoring and immediate action reduced hospitalizations and emergency visits, improving patient outcomes	5G	For chronic patients, the University of California, San Diego Health System deployed wearable 5G devices that sent real-time multisensory data to doctors
Telehealth with Augmented Reality	South Korea (2021)	Improved access to specialized care, patient engagement, and treatment plan compliance	5G	SK Telecom started 5G-enabled telemedicine using AR glasses for remote medical guidance during surgeries or therapy
Personalized Medicine	Germany (2022)	For personalized treatment plans, Charité—Universitätsmedizin Berlin collected and analyzed multi-sensory data using 5G and B5G	5G and B5G	Better patient outcomes, more effective therapies, and fewer negative medication responses
Smart Ambulances	UK (2022)	Early diagnosis and the start of therapy, better patient outcomes, and less traffic in the emergency room	5G	5G-capable ambulances with real-time data transfer to hospital specialists and diagnostic tools were tested by the NHS
Remote Physical Therapy	Japan (2023)	Improved healing rates and easier access to physical therapy services, especially in remote locations	5G	With 5G, therapists could remotely instruct and monitor patients' exercises utilizing multi-sensory data from wearable devices
Mobile Health Clinics	India (2023)	Reduced inequality in healthcare by improving remote healthcare access	5G	Underserved rural people received real-time diagnostic and consulting services from 5G mobile clinics
Virtual Reality for Pain Management	Australia (2024)	Reduced pain medication use, enhanced patient satisfaction, and improved rehabilitation outcomes	5G	A 5G-enabled VR system created immersive pain management and rehabilitation environments using multi-sensory data
Remote Mental Health Support	Canada (2024)	Personalized care and fast support improve mental health outcomes and reduce stigma and barriers to help	5G	Biometrics and environmental data were delivered in real-time for remote mental health consultations on a 5G platform
Advanced Medical Imaging	Italy (2024)	Faster, more accurate diagnozes, less patient travel, and better medical cooperation	5G and B5G	High-resolution medical imaging data was transmitted to professionals for remote diagnosis and consultation using 5G and B5G

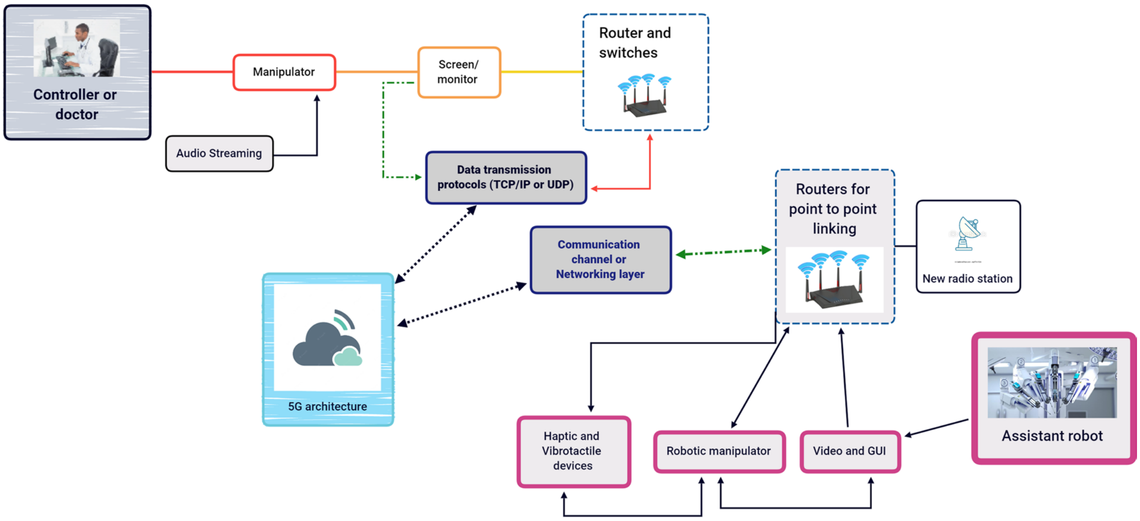

Fig. 5 General architecture of 5G enabled tactile internet

that beyond the previously mentioned thresholds can result in several issues, such as unpleasant handling sensations, responses, oscillations, and instability.

The Tactile Internet—where users can remotely interact with and modify results in real-time using haptic feedback enabled by 5G and beyond 5G networks—is made possible by the generic architecture shown in Fig. 5. The operator or user interacting with the far away society using haptic devices is represented by the Master Section. With its haptic interface, the user may manipulate, feel, and touch objects that are far away. The master element generates the control and feedback signals that need to be sent via the network. The Network Section covers the 5G (and beyond 5G) network architecture that enables the ultra-low latency and high-reliability transmission of haptic data. The slave section represents the remote setting or item that the user interacts with and manipulates in the master area. Included are actuators, sensors, and other components that can respond to haptic control signals and provide the necessary feedback. Table 8 provides information on tactile feedback signals and haptic device summary, with target audiences including type of patients for example students, and those with disabilities. Additionally mentioned is whether or not ROS has been used for the tasks carried out via the communication system.

9 Outcome and future research direction

5G, B5G, and 6G constitute advanced mobile communication technologies with a primary objective of enhancing data transmission, speed, and latency within wireless networks. Positioned as an intermediary phase between 5G and 6G, B5G, colloquially termed "Beyond 5G," is strategically focused on realizing high-speed data transmission and achieving ultra-low latency, marking a pivotal advancement in mobile communication evolution. The forthcoming 6G technology is conceptualized to facilitate terabit-rate data transmission, providing high-speed personal data links, and supporting vehicle-to-vehicle communication.

Both B5G and 6G technologies are purposefully designed to confront and overcome challenges posed by the evolving landscape, including the imperative of addressing higher system capacity, elevated data rates, reduced latency, and heightened security concerns [85]. In this technological trajectory, privacy considerations emerge as a critical focal point necessitating meticulous attention during the developmental phases of these advanced communication technologies. This underscores the importance of concurrently addressing privacy concerns to ensure the ethical and responsible deployment of 5G, B5G, and 6G technologies. In the future, Human-Bond Communication (HBC) will transform remote help by including gustatory, tactile, and olfactory sensations. Through virtual connections, this holistic approach enables healthcare providers to gather additional sensory data, improving their capacity to comprehend patients' health requirements in a better way [95].

This survey aims to provide an overall analysis and a general overview of multi-sensory transmission with a 5G-enabled network. The survey emphasizes that 5G and B5G networks significantly improve connectivity, and offer data transfer

Table 8 Summary of haptic devices and tactile feedback signals

Article Num	Haptic device	Tactile feed-back signals	Communication System	Target audience	Task Performed	ROS
[3]	Myo arm band	Force, position, velocity and stiffness	5 GHz Wi-Fi, UDP with 1 Mb/s and 18 Mb/s bandwidths	Any	Teleoperation, interaction and grasping object	YES
[29]	Valve Knuckle EV3	Position, motion and pressure	Arduino mega board	Students	Teleoperation, interaction and grasping object	NA
[30]	Controllers + vibrotactile motors HapTug	Force feedback Force and stiffness	NA	Any	Virtual reality	NA
[31]	An exoskeleton mechanism that fixes finger PHANToM	Force and torque feedback	Wireless communication	Any	Perception for grasping and manipulation	NA
[33]	ROBOTRAN (motion sensors) Gloveone gloves	Force and torque feedback (position, velocity)	Server based communication	Blind people	Navigate and explore the simulated 3D environment	NA
[34]	MG90s servomotor + HapCoil-One voice coil actuator	Position and motion	SSH protocol and physically via an ethernet cable	Road and railway, cranes, etc	Haptic piano key and driving simulator	YES
[35]			Cloud infrastructure (REST interface)	Phobia detected people	Remote phobia treatment	NA
[48]	Exoskeleton (wearable)	Force and vibration	USB serial communication	Any	Robotic Minimally Invasive Surgery Training Assessments	YES
[64]		Force and motion	NA	Any	Bilateral Teleoperation System	NA

speeds up to 10 Gb/s. This capability allows seamless transmission of multi-sensory data, which is a crucial application in healthcare which requires real-time data processing. The integration of 5G/B5G technologies like digital twins and multi-modal sensing enables innovative healthcare applications for instance tele-ultrasound, remote surgery and real-time patient monitoring. These use cases benefit from the low latency and high reliability of the networks.

9.1 5G and B5G

The main goal of 5G and B5G in multi-sensory data transmission is to enhance network capacity and data transmission speeds, while also boosting observability and connectivity for intelligent devices in wireless sensor networks [68]. These technologies are specifically developed to improve the process of collecting, analyzing, and utilizing sensory data in various environments by providing efficient data transfer, minimal latency, and reliable communication capabilities. In addition, B5G networks have been developed specifically to address the difficulties encountered by organizations relying on 5G networks. The issues include increased power consumption, limited accessibility of virtual mobile applications, excessive usage of multiple-input multiple-output (MIMO) in fixed wireless access, inadequate coverage of millimeter waves, and network instability. By leveraging the power of 5G and B5G technologies, organizations may enhance system performance, optimize networks for data transmission and storage, and ensure better connectivity and observability for smart devices in different settings [86]. In [37], Alperen Acemoglu et el used MEC/5G core network for telerobotic surgery.

The need to create a cellular control plane for core networks comes as a way to reduce the latency experienced by end-user applications. Neutrino was developed as a way to create a reliable cellular control plane for accessing cellular services. This is accomplished by building a connection between the IP network and the base stations, while at the same time giving priority to minimizing latency. The cellular control plane efficiently resolves the problem of providing reliable and fast access to the cellular core network by initiating connectivity sessions for each device. This is accomplished through the consistent updating of the user's position, which allows the user to access their data over the Internet or other services provided by the operator. The control plane follows uninterrupted tactics to minimize service disruptions in case of failures, guaranteeing those devices constantly maintain the capacity to receive read-your-writes consistency.

The latency of the control plane directly impacts the latency of data transfer. More precisely, the control functions that handle session formation can cause a delay of 72.5 to 99.6 milliseconds, which could result in a data access delay of up to 1.9 milliseconds. The advantages of integrating 5G communication into wireless sensing networks for AIoT (Artificial Intelligence of Things) applications include improved bandwidth, immediate data transmission, greater transmission efficiency, enhanced data integrity, compatibility with different sensors, and the potential to drive technological progress [49]. Yongpeng Shen et al in [50] mentioned that how 5G NB-IoT can be implemented for secure transmission in smart grid systems.

The study conducted in reference [74] examines the performance of Ethernet, WiFi, LTE, and 5G about their impact on teleoperation tasks. The evaluation of teleoperation performance is conducted by considering factors such as latency, reliability, and data transfer speed, with a special focus on maintaining system transparency. The experimental configuration

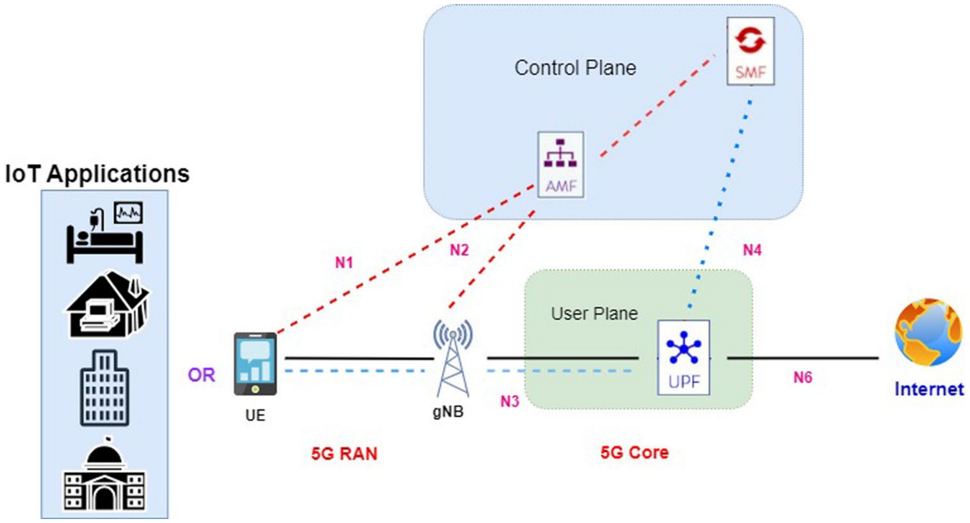

Fig. 6 General architecture of 5G network

includes Franka Emika robots and a motion-controlled human operator robot for systematic research. The study [74] pointed out the need to minimize communication delays and ensure the stability of telepresence systems.

Based on Fig. 6, In the context of 5G design, with a specific focus on sensor devices (UE) or IoT devices, the network components play a crucial role in ensuring uninterrupted connectivity and effective data processing. User Equipment (UE) deals with the electronic devices present in a network that interact with various network activities. The Next-Generation NodeB (gNB) acts as the primary station within 5G networks, enabling the link between the User Equipment (UE) and the core network. The Access and Mobility Management Function (AMF) has the responsibility of monitoring access and mobility for User Equipment (UE). It manages this by controlling responsibilities such as user equipment authorization and key distribution. The Session Management Function (SMF) is responsible for supervising session-related operations for User Equipment (UE), including tasks such as session establishment and maintenance. The N1 Interface acts as the link between the User Equipment (UE) and the Access Management Function (AMF). The primary objective of the NAS layer is to facilitate signalling, enabling direct communication between the User Equipment (UE) and crucial network services like AMF, SMF, and UPF. The N2 Interface functions as a connection between the RAN and AMF, enabling communication to manage mobility. The N3 interface functions as an intermediate point between the Radio Access Network (RAN) and the User Plane Function (UPF), enabling the transfer of user plane data. The N4 interface acts as a link between the SMF and UPF protocols, enabling session management functions related to data forwarding. The N6 interface acts as an interface between the User Profile Function (UPF) and the Data Network (DN), enabling the transfer of user plane data to external data networks like the Internet. The Control Plane (CP) includes the signalling and control functions that manage network resources, mobility, and session setup. The User Plane (UP) is responsible for managing the flow of user data between devices and networks.

9.2 Edge computing and multi-sensory framework

Edge cloud computing is commonly considered an effective strategy for dealing with the difficulties discussed above. Moreover, the deployment of processing and storage capabilities at the edge of the radio access network (RAN) leads to a decrease in latency for end users. To fulfil the high latency demands of virtual reality and augmented reality (VR/AR) systems, it is imperative to minimize the communication distance [94]. This goal can be achieved by implementing multi-access mobile edge computing (MEC), which requires bringing the applications closer to the end users. Mobile Edge Computing (MEC) is essential for enabling the deployment of 5G technologies. This is mainly due to its fundamental abilities, which include carrying out calculations and storing information at edge hosts located near the radio access network nodes, such as gNodeBs in the context of 5G. These processes are conducted in a decentralized manner, hence increasing the efficiency of MEC in facilitating 5G networks.

The decentralized structure of the network in Mobile Edge Computing (MEC) enables the delivery of low-latency services by providing a small and predictable delay between the end user devices and the server that hosts the application. The demanding requirements of AR/VR technologies allow challenges that can be resolved by the integration of the 5G-enabled Tactile Internet (TI) [91]. This method involves utilizing edge computing servers to process computationally demanding tasks, leading to communication with extremely reliable and sub-millisecond latency.

The TI, also known as the Tactile Interface, is an advanced device used in the field of Augmented Reality (AR) and Virtual Reality (VR) applications. The field includes several aspects like as sensors, actuators, robotics, computational components, and specialist hardware (e.g., wearable devices) [47]. The objective of this technology is to improve the sensory experience by offering tactile and haptic input, such as touch, visual, and audio, in Internet-based applications. In Figure 7, we wanted to show a specific layered multisensor edge computing architecture, with the cloud layer at the top, the edge layer in the middle, and the Internet of Things layer below. Time-sensitive sensor data can be immediately processed by the edge layer.

Edge computing optimizes the handling of multi-sensory input using several methods, resulting in benefits such as reduced delay, increased scalability, greater security and privacy, real-time analysis, and improved reliability. This improvement is accomplished by moving computational resources in closer proximity to the data sources, enabling faster, more reliable, and secure data processing. The close integration of these technologies is particularly advantageous for time-critical applications such as industrial automation, driverless vehicles, and augmented reality [59].

In addition, this method reduces the amount of data that needs to be sent over the network, resulting in greater network efficiency and a better user experience. In addition, edge computing efficiently handles data from several devices, reducing network congestion and decreasing latency. This characteristic makes it very suitable for Internet of Things

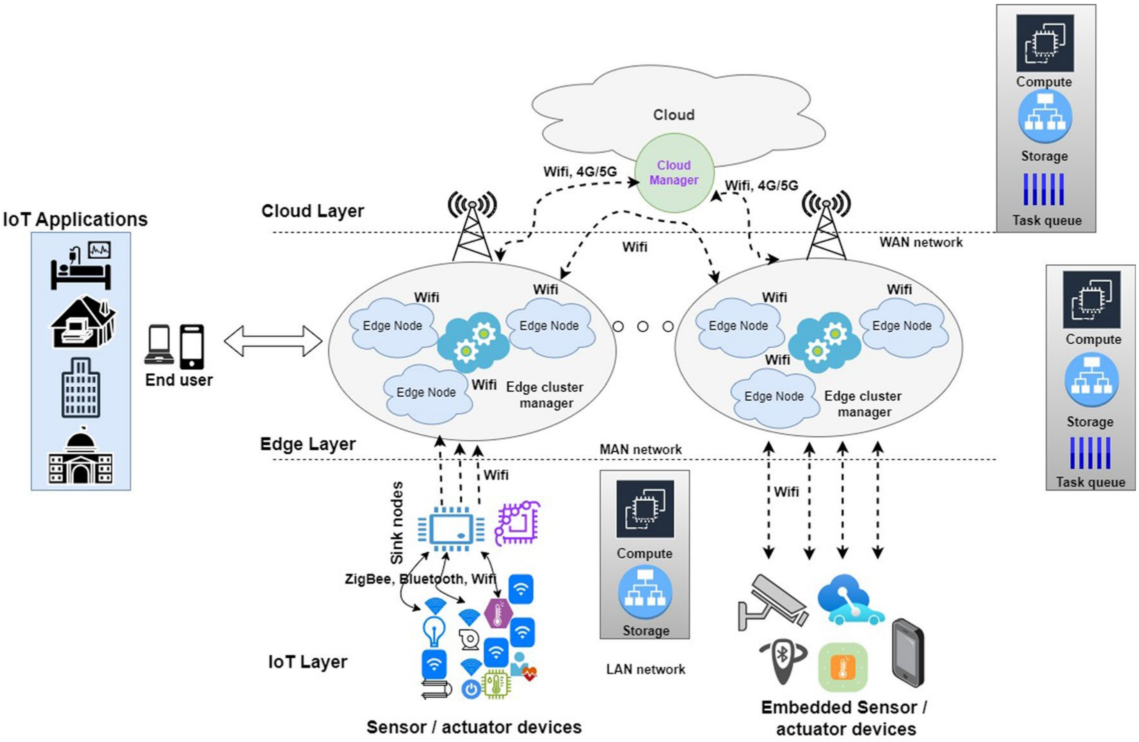

Fig. 7 Edge computing architecture

(IoT) applications, such as those encountered in smart homes or factory equipment, where significant amounts of data are created.

Edge computing technology enhances data privacy and security by processing and storing sensitive information directly on mobile devices. The reliability of edge computing is emphasized by its ability to process data at the source, resulting in fewer interruptions in service. Additionally, it can improve worker safety by monitoring and notifying workers of potential hazards in their surroundings.

9.3 6G and ML

The latency requirements for an augmented reality/virtual reality (AR/VR) system involve the necessity of a quick and responsive remote environment, frequently indicated by a latency range of 40ms to 300ms. This allows the system to provide improved visual content, such as greater resolution, frame rate, dynamic range (HDR), and a 360° spherical six-degree-of-freedom (DoF) experience. eMBB, within the framework of 5G technology, plays an important part in enabling a greater bandwidth than the prior version, 4G. It is important to note that the ability of eMBB to improve low-latency performance is slightly restricted, but it can still maintain the appropriate bandwidth capabilities.

Therefore, the current issue requires the use of ultra-wideband (UWB) wireless technologies to enable a system with minimal delay that can be efficiently used in high-quality audio and expanding augmented reality/virtual reality (AR/VR) applications. This is accomplished by enabling prompt transmission with enhanced data transfer capability. The UWB system requires an appropriate antenna design that can cover both traditional LTE and sub-6G bands simultaneously. This specific design requires an interface that covers both line-of-sight (LOS) and non-line-of-sight (NLOS) situations, combined with creative hardware designs that aim to fulfil the bandwidth requirements of 6G networks. This can be done by using radio-frequency (RF) micro-electromechanical-system (MEMS) enabled terahertz switches, which allow for the manipulation of a wider range of frequencies while reducing the time it takes to react.

6G networks will be expected to provide the necessary framework for smooth and reliable communication between physical systems and the Internet of Things in the context of transmitting multi-sensory data [75]. These networks will provide the necessary high data speeds, low latency, and quality of service to enable real-time interactions between physical and virtual devices. To precisely imitate the actions of human counterparts in different sensory modes, machine learning methods will be utilized to analyze the variety of information collected from various sensors and sources. Digital twins can reproduce the qualities and behaviors of human counterparts in real-time scenarios more accurately by integrating data from several sensors, including distributed sensory inputs and 3D maps. Gerhard P. Fettweis and Holger Boche analyze recent developments in mobile technology and explore the potential of universal remote-controlled mobile robotic systems [84]. Additionally, they investigate the influence of information and communication theory on the development of 6G technology.

The Key Performance Indicators (KPIs) of 5G and 6G technologies display numerous variations. The key performance indicators (KPIs) for 6G include many metrics such as maximum bandwidth, experienced data rates, peak data rates, area traffic capacity, network energy efficiency, peak spectral efficiency, experienced spectral efficiency, latency, jitter, dependability, and availability. Two specific key performance indicator (KPI) values for 6G technology are a peak spectral efficiency of 60 bits per second per hertz (b/s/Hz) and a peak data rate of 1 terabit per second (Tb/s).

Machine learning (ML) is applied within this structure of digital twins to achieve various goals, including optimization, prescriptive analytics, and diagnostic and predictive analytics. Machine learning (ML) models enable the study of real-time sensor input, prediction of behaviour, diagnosis of problems, prevention of failures, and optimization of system performance. These responsibilities are based on historical data and limitations. Generative artificial intelligence, specifically Large Language Models (LLMs), has a vital role in the progress of the Internet-of-Senses (IoS) using 6G technology [92].

5G and B5G networks provide enhanced connectivity, reduced latency, and increased reliability compared to earlier generations. This enables seamless transmission of multi-sensory data for healthcare applications. 5G and B5G can greatly overcome the high bandwidth requirements of multi-modal sensing in the healthcare sector, with data transfer rates reaching up to 10 Gb/s. Within healthcare environments, the integration of 5G/B5G technology with digital twin technology and multi-modal sensing enables greater communication and monitoring of intelligent equipment. The features of 5G and B5G enable the development of innovative healthcare applications such as tele-ultrasound, remote robotic surgery [77], and real-time patient data monitoring.

Further research is necessary to enhance the 5G/B5G network structure to better fulfil the specific needs of healthcare applications, such as the smooth integration of multi-sensory data and highly dependable low-latency communication. Studying advanced techniques to integrate and analyze data from different sensory inputs, including physiological, audio, and visual sensors, to improve the effectiveness and precision of digital models in healthcare. Our goal is to showcase the secure sensitive patient data transmitted across 5G/B5G networks by implementing robust security and privacy measures, thus ensuring the confidentiality and integrity of multi-sensory healthcare data. Exploring the intersections and synergies of 5G/B5G, digital twins, machine learning, and other advanced technologies to enhance the transmission of multi-sensory data in the healthcare industry.

9.4 Outcome and lessons learned

This survey highlights the significance of developing robust security and privacy measures to protect sensitive patient data transmitted over these networks. Moreover, a detailed description of protocols used for the multi-data transmission would be helpful in understanding the security measures during real-time monitoring. The challenges posed by different sensory modalities are included here and addressing them is essential for varying requirements for sampling, transmission rates and latency.

We presented common operational challenges encountered in the transmission of multisensorial media provided by 5G technology. Subsequently, a comprehensive analysis and practical examples were provided, addressing the widely used haptic devices and the existing challenges associated with teleoperation systems. The present study includes a thorough compilation and qualitative assessment of transport and network layer protocols that provide multi-modal communication. Specific attention is given to the effective management and synchronization of haptic, video, and audio data streams. Presenting the most substantial ultimately, we explored the necessity for enhancements using cutting-edge approaches in multisensory transmission via 5G networks.

For instance, we identified AI/ML, edge computing, and 6G as the next areas of investigation in multimedia transmission strategies. It emphasizes the considerable capacity of 5G and B5G networks to augment the transmission of data in real-time, boost patient monitoring, and facilitate telemedicine through the provision of reduced latency and increased bandwidth. Nevertheless, the study also highlighted obstacles such as the expenses associated with infrastructure, the need to integrate with current healthcare systems, and the need to guarantee data security and privacy. The findings highlight the necessity of ongoing research and innovation to tackle these issues, as well as the requirement of establishing strong regulatory frameworks to capture the advantages of these sophisticated networks in healthcare properly.

10 Conclusion

5G to B5G or 6G improvements to networks have the potential to completely transform healthcare by improving connection, observability, and technology. To facilitate the seamless integration of multi-modal sensing technologies and provide real-time processing and analysis of contextual data from connected devices, B5G networks offer increased data transmission speeds, low latency, and high dependability. The advancement in network technologies will ultimately improve patient care results, and system performance, and streamline healthcare operations by providing quick and on-the-spot reactions. This advanced network technology adoption in the healthcare industry has a lot of potential, even though there are still certain obstacles to be addressed. We demonstrated some frequent implementation issues for 5G-enabled multisensorial media transmission. Following that, a broad comparison and case studies were given, covering the commonly utilized haptic devices as well as the current difficulties with teleoperation systems. Additionally, all transport and network layer protocols that, support multi-modal communication have been listed and qualitatively evaluated, with a particular focus on the management and synchronization of haptic, video, and audio data streams. In the end, we discussed the need for improvements with the latest methodologies in multisensory transmission over 5G networks for example AI/ML, edge computing and 6G will be the future study scope in multimedia transmission.

Author contributions As a single author and written by only single author, Purva Joshi, I am taking full responsibilities for full article. I have written each and everything by my own, without using any AI writing tools. I used Grammarly in overleaf for correction of my spelling and grammar mistakes. This article is about survey and review of studies done, not about any research activities carried out by me. I accept and responsible for full article submission and publication.

Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

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