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Tactile IoT and 5G & beyond schemes as key enabling technologies for the future metaverse

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Abstract
The Tactile Internet (TI) is a recently emerging field that has been developing and evolving to date, since its communications parallel the sense of human touch. Lately, the revolutionized concept, Metaverse, draws attention due to the evolved immersive experience of human perception of the surrounding environment. This technology supports the ultimate union between the physical and virtual world, facilitated by 5G and beyond communication networks. Users are capable of interacting with machines and devices in real-time, remotely, resembling the actions of their physical counterparts. The particular approaches are still in their infancy and expected to produce spectacular results in various sectors such as industry, healthcare, autonomous vehicles, etc. This immersion is further assisted by the Internet of Things, while expecting full wireless support by 5G networks. In this article, a systematic review studies the domains of TI, 5G and beyond networks, as well as their relations with the Metaverse, rendering the respective schemes Key Enabling Technologies for the future Metaverse. A thorough analysis is conducted on the underpinning schemes, relative architectures, structures, and operation modes. In addition, a comprehensive list is presented, focusing on related application fields and their benefits, considering the strengths and weaknesses of the involved technologies. Finally, challenges and issues arising are discussed, both from the perspective of technical requirements and the psychosomatic aspect of human experience.

Keywords Tactile internet · Tactile IoT · 5G and beyond · Artificial intelligence · Metaverse · Extended reality · Immersive Internet · Augmented/virtual reality · Review

1 Introduction

Tactile Internet (TI) is a new field that emerged in 2014, earning attention for the potential of changing human's mindset toward daily-life actions. Coupled with Metaverse technologies, interactions with machines and the virtual world are pushed beyond norms and boundaries. A significant example is Haptic's reference to human touch, focusing on humans' perception and manipulation of objects [1, 2].

Generally, various definitions have been given for the TI. The International Telecommunication Union (ITU) defines TI as an Internet network that combines ultra-low latency, extreme broadband, security, reliability, and increased availability of high-speed Internet connectivity, which is facilitated by the utilization of fifth-generation (5G) communication network technology [3]. It is expected that machines will have the ability to mimic human reaction speed, thanks to the low latency provided by high-speed Internet connections. The Tactile IoT (TIoT) is considered to be a successor of the Internet, which through enormous technological advancements resulted in the development of IoT, and consequently in its related subfields, including Industry 4.0 (I4.0) and Industry 5.0 (I5.0) [4]. Fettweis defined TI as the technology capable of affecting the Global Economy and daily life [6], by controlling and directing real and virtual objects through the Internet with enabled low round-trip latency [5]. Another approach presented in [7], defines TI as a remote access network, allowing users to perceive, manipulate and control real and virtual objects in real-time.

The term Metaverse can be referred to as an open ecosystem of software and hardware, indicating the transformation of physical objects into their digital counterparts, aiming

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toward an improved and upgraded Internet network. Generally, it constitutes a 3D virtual space, promoting working, socialization, and entertainment [8]. It is supported by state-of-the-art technologies and efficient devices, assisting the union of the physical and digital world, while allowing users and things to interact intuitively through complex systems. From a technical standpoint, it consists of multiple programs and processes, where information transits via network communication protocols, connecting users in the form of avatars, allowing asynchronous or real-time communication, as well as business and commercial engagements (personal identity, social connection, data storage, content creation and distribution, payments).

It is understood that TI and Metaverse are two highly related technologies that complement each other, with success lying in the capabilities of next-generation networking, and specifically 5G and beyond systems [9]. 5G offers high-speed connectivity, data streams, and reliable fixed connections, compared to previous generations. A one-millisecond end-to-end latency is a prerequisite for tactile communications and therefore sufficient capacity and minimized total delay are required to expedite vast communication links across a large number of autonomous devices. Since most of the processing occurs at the edge, underlying network infrastructure is needed to support the fast handling of the content and data. The edge allows content to be stored in cache and vast amounts of data to be processed locally, such as audio, video, and haptic information from devices and sensors. 5G satisfies the required prerequisites due to a latency time of under two milliseconds and fast data sharing [10] while providing enlarged coverage, faster communication, and high capacity [11, 12]. Thus, it becomes evident that TI and 5G and beyond schemes rise as promising Key Enabling Technologies (KET) for the future Metaverse.

The methodology followed in this work is a systematic literature review. The platforms Scopus and Google Scholar were used to search for relevant peer-reviewed journal publications and conference proceedings, focusing on publication years between 2009 and 2022, and indexed by databases such as Elsevier, Springer, and IEEEXplore. The keywords used in both platforms are: “Metaverse”, “TIoT”, “5G Metaverse”, “Metaverse Applications”, “Haptic communication 5G”, “Metaverse threats”, “Metaverse security”, “5G TIoT”, “Metaverse Architecture”. The total number of papers gathered for the conduction of the systematic review is 130.

1.1 Article contribution

Through the years, a part of the academic community has been highly focused on the innovative fields of IoT and TI, 5G, but also on the concept of Metaverse. According to the existing literature, the majority of researchers focus on the requirements and architectures, which they often conjecture, as well as their experimental applications. Although the provided conclusions are significantly interesting, the results are derived from researching the technologies separately. Therefore, to date, there is no integrated published research investigating the combination of the technologies mentioned above.

In this paper, the contribution lies in the combination of the Metaverse, TI, and 5G communications networks and beyond. Their concepts are thoroughly analyzed by studying their architectures, requirements, and implemented communication protocols, with informative comparisons when possible. In addition, their capabilities, benefits, and limitations are indicated, due to the lack of logistical infrastructure. Finally, there is a discussion about the impact of this new technology, taking into consideration all of its aspects, both from a technological and human psyche point of view, as well as highlighting challenges and issues that arise. Furthermore, as part of our research we attempt to answer the following research questions critically:

RQ1: Under what conditions are the 5G communications, IoT, and by extension, the TI with Metaverse incorporated?
RQ2: What are the requirements for developing such systems and to what extent will they be reliable and effective?
RQ3: What should be their architecture and structure?
RQ4: How do the 5G and beyond networks contribute, and why are they considered significant?
RQ5: What are the limits, benefits, and limitations of these technologies?
RQ6: How does the use of these systems affect psychosynthesis and human perception?

1.2 Related work

TIoT and Metaverse are gaining more and more ground to this day. Nowadays, the field of TI combined with the development and evolution of 5G networks, is considered an important contribution to the Metaverse. Therefore, big challenges arise for researchers who are interested in devising methods and techniques for the architecture of related systems, aiming to solve complex problems in a short time and with high precision.

As mentioned above, it was concluded that there is no available material covering the combination and related aspects of both TI and Metaverse technologies. These surveys are defined and categorized by their focused research elements, such as software, requirements, structure and architecture of systems, communication protocols, and applications, general tutorials, and challenges.

In the study presented in [5], researchers attempted to define the TI through visual scripts to highlight the challenges that arise. Another study [13] presents the vision of the Haptic Internet and its effects, comparing it with mobile Internet and IoT, whereas in [14], researchers describe the challenges of TI and provide hints to address them. The authors of [1] and [15] focus on the TI based on a 5G environment and highlight its special features with application examples (e.g., education and healthcare applications) and the architectural components in the primary, network, and secondary domains. In [16], the authors present haptic communications from psychological and technical perspectives. Other researchers are focused on the integration of TI with technologies such as fog computing [17], edge computing [18], networks based on software [19], IoT systems [20], 5G architectures [21], and algorithmic solutions [4].

On the other hand, research on Metaverse is mainly focused on the concepts and infrastructure of corresponding systems. Duan et al. [22] present applications about infrastructure, interaction, and the overall ecosystem, while identifying three layers of the architecture of the Metaverse. Messinger et al. [23] discuss the simultaneous interaction of people in a virtual world, applied to different sectors such as business, education, and social. Müller [24] characterizes the world as an electronic memory and the Internet as a virtual reality, which enables users to act safely. Dionisio et al. [25] discuss the Metaverse's access, identity, interaction, and scalability concerning realism. In [26], the author attempts to introduce a different term for the Metaverse ontology, and in [27], researchers study different approaches to Metaverse-related definitions.

The structure of the survey is organized as follows: We first introduce the research topic in broad terms, its contribution scope, as well as previously related published research. Section 2 investigates the development phases and historical evolution of the Metaverse and TIoT. Section 3 analyzes the conceptual frameworks, architectures, features and components while comparing the IoT and TIoT technologies, and the related communication protocols. Section 4 studies the applications of these technologies, and fundamental security mechanisms and threats. Section 5 focuses on the advantages, limitations, and emerging challenges of the corresponding technologies. We close the article with Sect. 6, where we carry out our conclusions, potential future directions, and open issues.

2 Historical evolution of IoT and the metaverse

TI and Metaverse are recent concepts that foreshadow the merger of an ideal 3D space with the physical world. One issue that bothers man since the earliest years is 'truth' and the realism of this new world. Plato's "Allegory of the Cave" is a concept devised by the philosopher about the perception of the world, and the truth between the physical and virtual realities [28].

First of all, when referring to the development and evolution of new technology, it is impossible to determine its respective timeframe. Technologies are a mix of different fields and innovations, complementing each other, and aiming at developing more efficient systems, with optimal decision-making programming.

Before analyzing the historical development of TI, one issue of concern is its origins in terms of predecessor technologies. Therefore, it is considered appropriate to indicate the development and evolution of the Web. Figure 1 depicts the development and evolution of the Web, from the initial syntactic Web towards the forthcoming 5G-enabled TI and the Metaverse.

The first version of Web 1.0, referred to as Syntactic, was limited to "read-only" content and powered by technologies such as Digital Libraries and Databases, Personal Hypertext Preprocessor (PHP) code in Hyper Text Markup Language (HTML) utilized for the development of dynamic and interactive web pages, and Hypermedia.

Web 2.0, referred to as Social Web, was highly user-focused while providing the capability of online interaction, communication, and sharing of created content on social media or video streaming platforms, such as Facebook, or YouTube respectively.

Web 3.0, referred to as Semantic Web, introduces the concept of "ontology", which is the backbone of functionalities such as information interpretation via Artificial Intelligent (AI) and Machine Learning (ML), and intelligent suggestion of related searched keywords through Google Search. In addition, new models are implemented such as Uniform Resource Identifier (URI) for the identification of real-life objects, people, locations, concepts, or information resources, and Resource Description Framework (RDF) for the depiction of interconnected data on the web metadata exchange.

Currently, IoT is considered a significant research trend due to the development of high-availability applications, that can be accessed and managed by a vast number of devices and software platforms, supported by communication protocols such as Machine-to-Machine (M2M) which is the foundation of IoT. Simultaneously, TIoT is a continuously emerging technology, where users utilize a combination of smart devices, sensors, actuators, and secure haptic devices, for real-time remote communication, through protocols such as Human-to-Machine (H2M) [29–32].

Up until the advent of IoT, the physical and virtual worlds were connected due to the interconnection of billions of computers via the Internet [33]. Similarly, 5G assists in feasible haptic interactions, where relevant communication infrastructures are available. These interactions require low latency

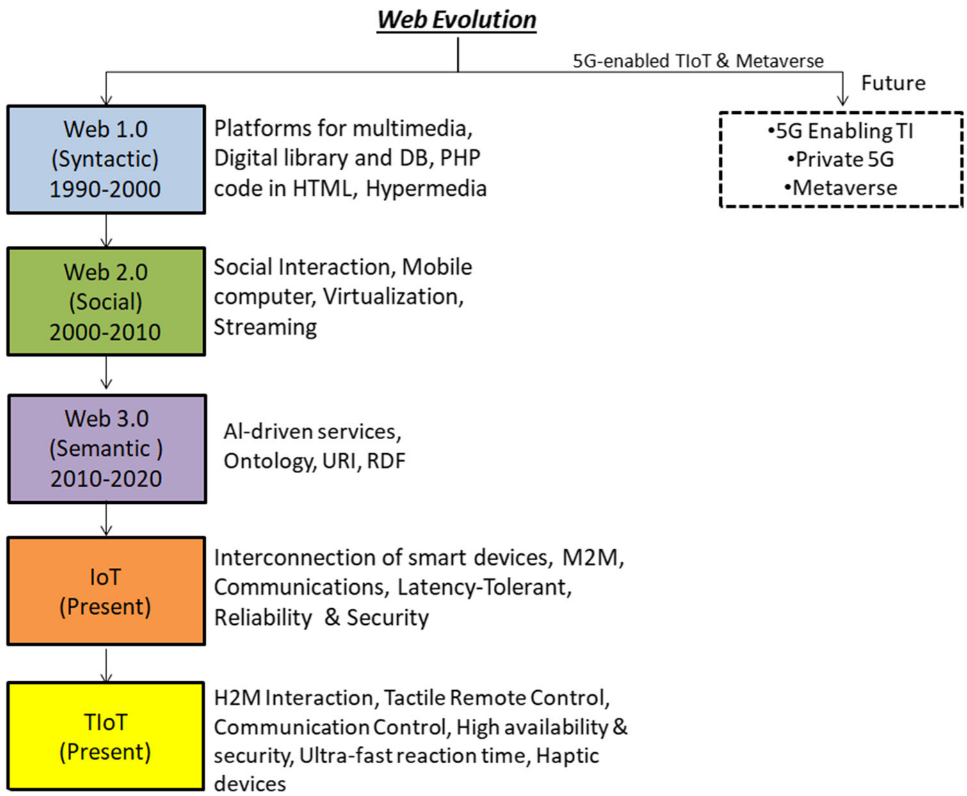


Fig. 1 Development and evolution of the Web towards the Tactile IoT and the Metaverse

transmissions, so 5G supports systems transitioning from IoT technology to TI [17].

The revolution of the TI begins with mobile internet networks (e.g. 2G, 3G, 4G, and 5G), with generation featuring its own characteristics. First generation (1G) networks utilized packet radio services (GPRS), enhanced data rates for Global System for Mobile (GSM), and evolution (EDGE). These technologies have successfully managed to connect numerous users, smartphones, and laptops across the globe.

Today, 5G networks support Human-to-Human (H2H) interactions for data, multimedia content, and signal exchange, while providing full functionality for IoT applications when combined with Device-to-Device (D2D) protocols [34]. IoT is defined by its interconnection capabilities, D2D communication, collection of sensing data, and data analysis during an interaction. Furthermore, it provides low latency, low rate, reliability, security, and real-time remote control.

On the other hand, TI combines ultra-low latency, high scalability, availability, security, enhanced reliability, and responsive connection [1]. It revolutionizes various sectors such as healthcare, education, and industrial fields. Moreover, it supports Human Interface Systems (HIS) and successful interaction through smart haptic devices for communication purposes, or gaming content development based on Virtual Reality (VR) and Augmented Reality (AR) technologies [35]. Figure 2 presents the evolution of TI to Mobile Internet and IoT.

The Metaverse is centered around H2M and M2M interactions assisted by haptic devices with remote touch functionality thanks to the ultra-reliable and ultra-responsive network of TI. However, each technology contributing to Metaverse provides its own unique features. IoT supports only M2M interactions, enables Blockchain technologies, and is capable of empowering smart devices with AI. TIoT implements HIS and the functionality of smart haptic devices. 5G and beyond systems provide ultra-low power consumption and latency, numerous device connectivity options, security, resiliency, and scalability. Though, only Beyond 5G (B5G) systems provide enhanced Mobile Broadband (eMBB), Ultra Reliable Low Latency Communications (URLLC) for network connectivity of sub-millisecond latency for applications such as remote surgery [36], drone navigation [37], pedestrian navigation [38], and industrial applications [39]. Figure 3 shows the differences between IoT, 5G, and TI while listing their common features.

Overall, the concept of the Metaverse first appeared in a science fiction novel. Thirty years later, it resurfaces again as a buzzword and embodied version of the Internet, beginning in the form of online gaming platforms [40]. Figure 4 presents a short timeline of the Metaverse, signifying the landmarks of its technological development.

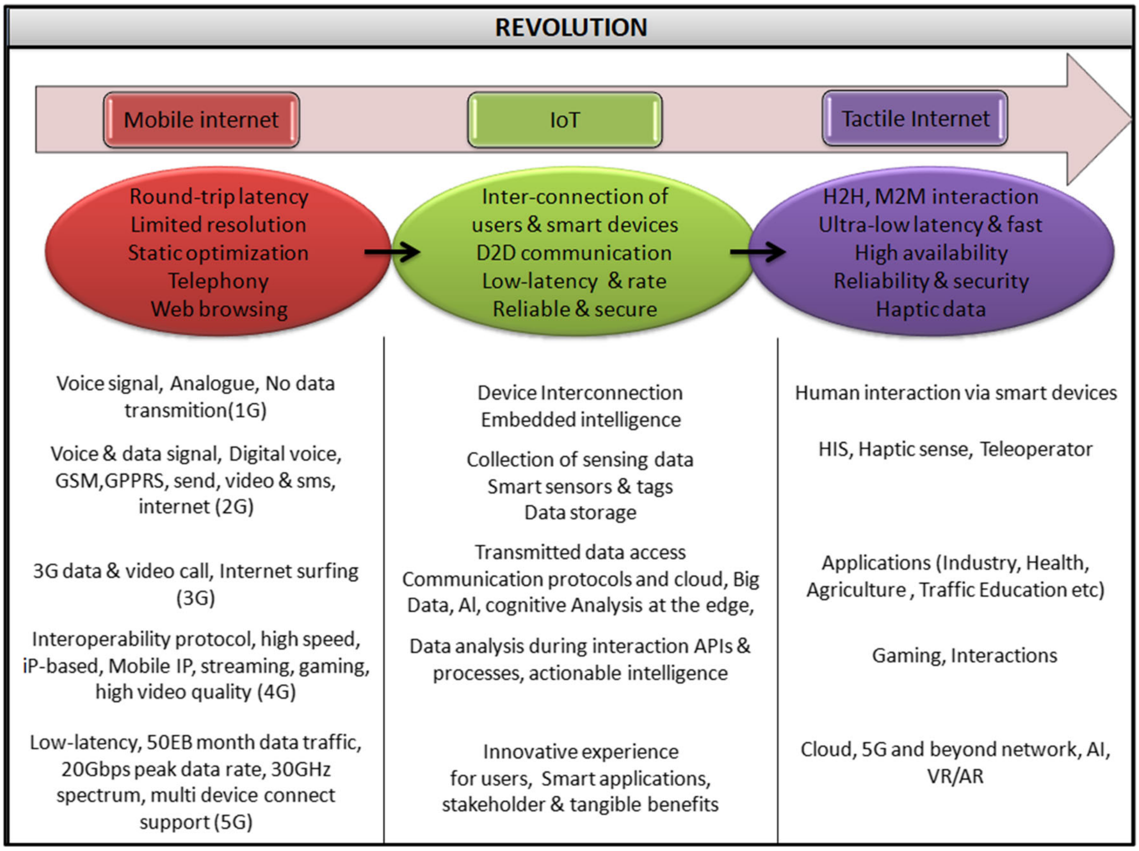
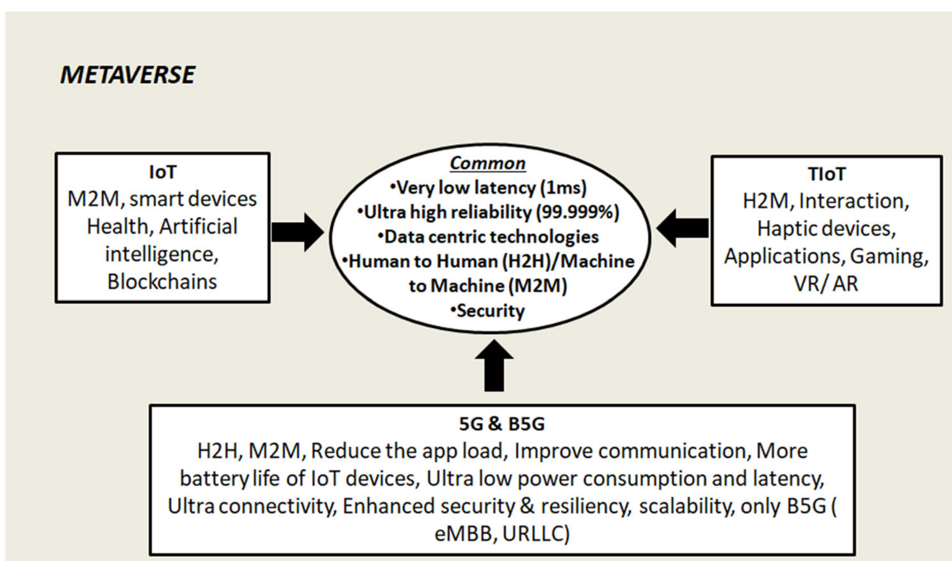


Fig. 2 Evolution of Tactile Internet

Fig. 3 The common features and differences of IoT, 5G, and TI in the context of Metaverse



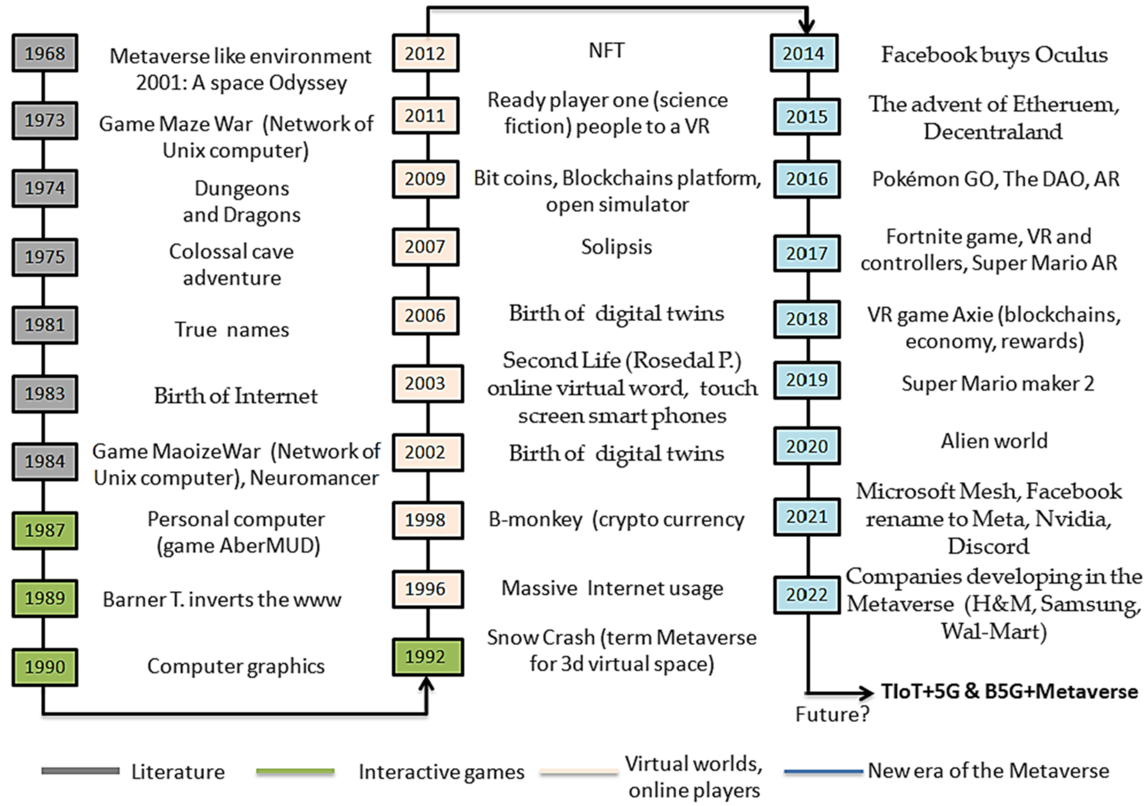


Fig. 4 Timeline of Metaverse

3 Conceptual frameworks of metaverse, 5G and beyond, and TIoT: current status

3.1 5G-supported conceptual framework of metaverse

The idea of the Metaverse was born in 1992 by N. Stevenson, in her science fiction novel "Snow Crash" [41]. The etymology of the word is derived from the prefix "meta" (implying transcending) and the word "universe", describing a virtual environment linked to the physical world [42].

In Computer Science the term Metaverse is an online, 3D virtual space that connects users in all aspects of their lives [43]. In the broad sense, the Metaverse is a 3D virtual environment simulating the physical world to the fullest extent, where users act as they would do on a casual basis (political, socio-economic, and cultural activities) [44–46].

There is general confusion due to the similarities of the Metaverse with virtual reality and augmented reality. However, a major difference is the existence of virtual and augmented reality as part of the Metaverse, but not as a prerequisite, since many applications in the Metaverse can function without these technologies [47]. Moreover, there is a strong correlation between the Metaverse and IoT technologies. IoT will enable Metaverse to interact with the real world, while Metaverse will act as a 3D user interface to IoT devices. An indicative example is the company Meta, which is developing a Metaverse environment for users and players to co-exist in a vast network of real-time 3D virtual worlds while maintaining identity privacy and transaction history.

The ultimate goal of the Metaverse is interconnecting multiple platforms, containing different web pages that are accessible through a single browser and guided by elements of augmented and virtual reality while performing the corresponding interactions by assuming the form of a customized avatar. The key technology associated with the Meta-Universe is 5G, which constitutes a critical enabler for the Metaverse, its devices, and the application developer ecosystem, as shown in Table 1 [48, 49].

3.1.1 5G and beyond features enabling metaverse connectivity

5G provides the required latency and throughput for a fully functional remote experience, with accelerated support by automated technologies such as Web 3.0, Blockchains, and smart devices. In addition, 5G networks support high data transmission rates in the range of Gbps, with very low latency (below 1 ms) and enhanced reliability level of five 9's (99.999%) for Metaverse applications [50], and provides

Table 1 Requirements of Metaverse related to 5G and beyond networks

Networking requirements	5G and beyond support
Access to all multiverse forms	Coverage, capacity, mobility
Lightweight and accessible XR devices	Low latency, reliable communication, Access to edge compute with high throughputs and low latency
Cloud and Edge-Cloud (MEC) capabilities	Offload processing for battery life efficiency Enhanced render Level of Detail (LOD)
Standardized interfaces	Telco, Metaverse, Haptic, holographic, XR standards
Easy access to communication services	APIs giving access to 5G as a network platform Easy bind on APIs/SDKs into platforms

frequency bands in various parts of the frequency spectrum, defined into FR1 (4.1–7.125 GHz), focused on processing and managing traditional cellular mobile data traffic, and FR2 (24.25–52.6 GHz) focused on high data rate functionality in a short-range [51]. Table 1 presents the requirements of the Metaverse as well as the related potential of 5G and beyond technologies.

Standards and standardized interfaces ensure interoperability within the complex Metaverse ecosystem, considering the implementation of Blockchain technology, virtual worlds, and haptic devices. The IEEE Haptic Codecs standardization group P1918.1.1 develops codecs for kinesthetic and tactile signals; also called "MPEG of touch". Several examples of related standards are available, such as 3GPP [52], ETSI [53] ARF [54], and OpenXR [53]. However, the main challenge is the maintenance of interoperability between virtual worlds, which is akin to the transition from LANs to today's Internet [55]. IoT and sensor networks collect data from the physical world to update the virtual environment, with the digital counterpart utilizing AI algorithms through software representations of a physical system [56]. The sensor networks may be owned by independent providers which contribute live data feeds [57] to virtual service providers (VSPs) to maintain the environment or object of interest.

The impact of Metaverse on IoT lies in two aspects related to the use of Digital Twins [58]. The first one is enhanced, real-world training, where extreme situations are possible through simulations by using Digital Twins in the Metaverse, improving problem detection and decision-making. The second aspect is dedicated to smarter long-term planning and short-term response rate. As a result, the Metaverse will provide an effective reflection of the physical world, while implementing various long-term planning scenarios, assisting users to respond to ongoing events, and utilizing A.I. for proper learning and prediction of expected results on complex problems [59].

3.1.2 Structure, components and features of metaverse

Currently, there is no specific structure for the meta-universe. Although some requirements and elements of these new systems have been investigated [60–62], further research is needed for additional required tools and infrastructures, to improve efficiency, reliability, and safety. Figure 5 provides an aggregated presentation of the foundations, requirements, infrastructures, features, components, and ecosystem of the Metaverse. In addition, the user's experience and the impact of the corresponding technology on their psyche are listed.

3.1.3 Basic architecture of metaverse

The Metaverse, depending on the utility purpose, consists of several layers. However, its general form includes at least three basic layers (physical, virtual, and technical) that support the real-time interaction of users in the physical-virtual world [63]. In the virtual world, users are capable of creating a 3D avatar and experiencing various virtualized scenarios such as virtual performances, virtual dating, and 3D telecommuting. This interconnection of the Metaverse and the physical world, including devices (e.g. headsets, VR haptic gloves, access points) and communication mechanisms at the edge of the network are supported by physical network providers [64]. Generally, the architecture of the Metaverse is considered an exclusive research topic, since it does not include a defined structure; nevertheless, categorization of the physical and virtual worlds, as well as their intersection can be made. Table 2 lists the various architectural aspects of the Metaverse, taking into account as many parameters as possible.

In addition, another type of architecture that could be considered is related to the learning process of the Metaverse. Figure 6 depicts the levels and components of the respective learning model.

3.2 Conceptual framework of TIoT

The data collection by sensors is facilitated by faster Internet connections and increased bandwidth [65]. Tactile IoT allows humans and machines to interact in real-time with ultra-low latency, high availability, and efficiency (reliability, security, availability, and authentication).

Following this concept, the interaction succeeds via various technologies and applications in the network of the established connections. At the edges, the Tactile IoT is enabled by the sensors, actuators, and robotic "things", while data are transmitted over a 5G network. The IEEE P1918.1

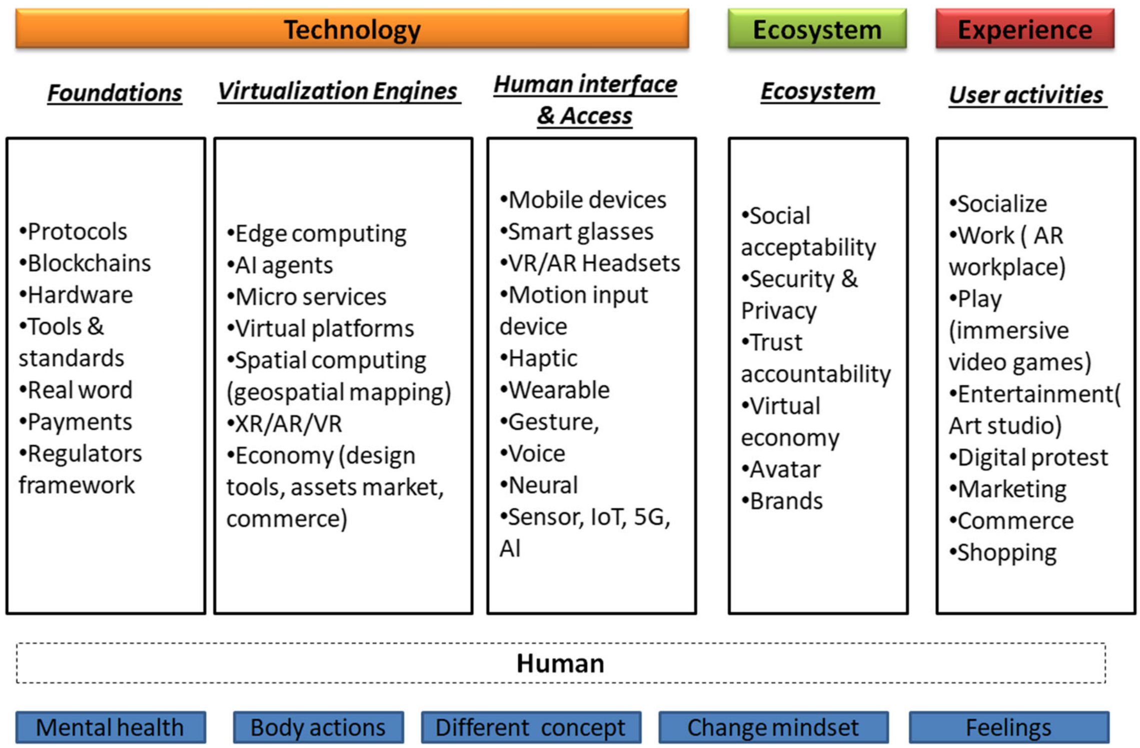


Fig. 5 Factors and parameters of Metaverse

defines the TI as a "network or network of networks for remotely accessing, perceiving, manipulating or controlling real or virtual objects or processes in real-time by humans or machines", with this process facilitating and harmonizing the interaction between two worlds [66]. Haptic feedback allows users to perceive objects through VR via audio-visual or touch. The physical simulation and display rates of haptic information are in the range of 1000 Hz with a communication latency of 1 ms [67]. Moreover, Tactile IoT requires latencies less than 1ms, distributed in distances larger than 200 km, utilizing a low-latency IoT core network [68].

The main architectural requirements are accomplished by storing tactile applications locally and by reducing end-to-end latency from sensors to actuators for scalable procedures at all protocol layers [69].

In the future, it is expected that mobile IoT, robotics with AI, and cloud technologies, will be combined thanks to Fiber-Wireless (FiWi) resulting in enhanced Human-to-Robot (H2R) interactivity, and potential economic impact [70].

3.2.1 Design and components of TI

As mentioned above, the technology of TI is based on running various applications dedicated to man–machine interactions, and touch in real-time. This interaction has different reaction times for audio, video, and manual interactions which amount to 100, 10, and 1 ms respectively since each application is special and unique. Thus, the construction components of the system may vary depending on each use-case scenario.

However, the overall construction of such systems is defined by a common framework corresponding to the involved components. TI requires responsive connection, ultra-reliability, and low latency for implementation in sectors such as healthcare, smart systems, etc. In this case, reliability means the availability of communication services, which should amount to almost 100%, security and privacy by designing new mechanisms and algorithms. Proper identification of authorized users in fully connected applications, as well as efficient management of tactile data, such as touch sensation along with audio and visual data, are considered significant attributes and challenges [71, 72]. Figure 7 depicts the corresponding technical requirements.

3.2.2 Haptic communications, data, and protocols

The term haptic is a Greek word meaning "aptiko" [67], and by analyzing the etymology of the word it translates into the human perception of touch (the sense of touch). Haptic communications are achieved through the communication channel where physical sensations and controls are transmitted remotely in real-time. Constructing a tactile network requires haptic and tactile devices and displays, as well as teleoperators (robot or human) to allow ultra-reliable and

Table 2 Parameters and technologies of Metaverse

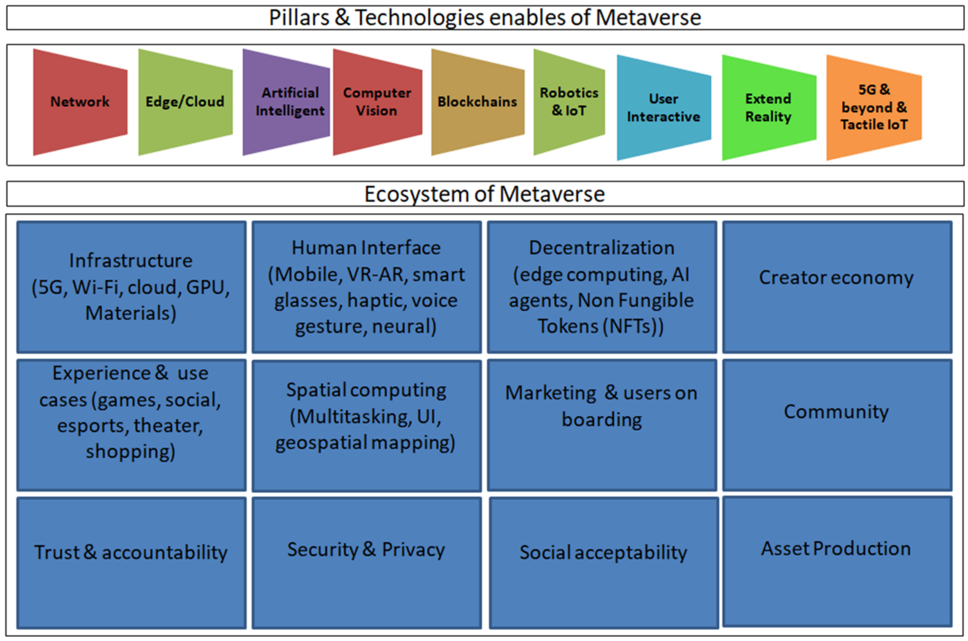


Fig. 6 Features and components of learning Metaverse

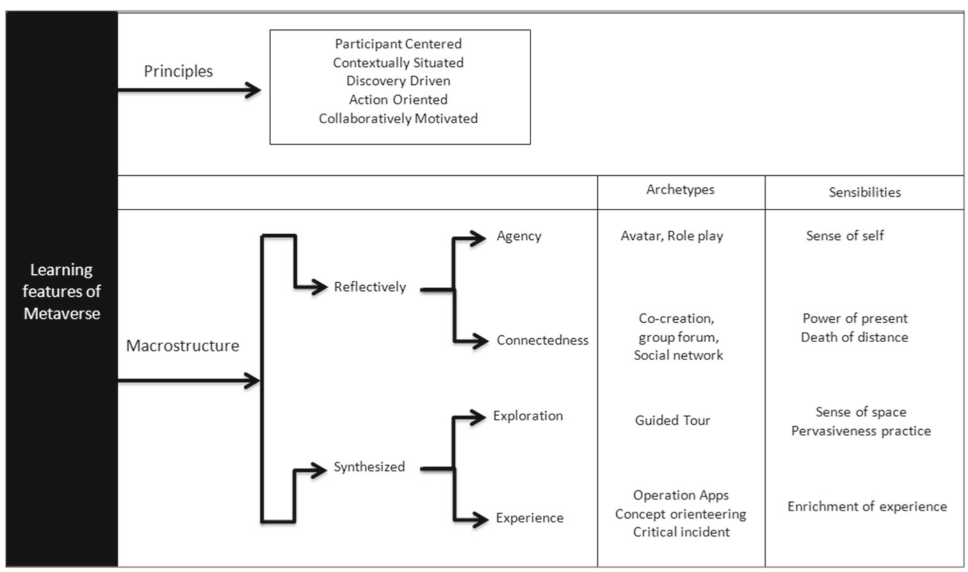
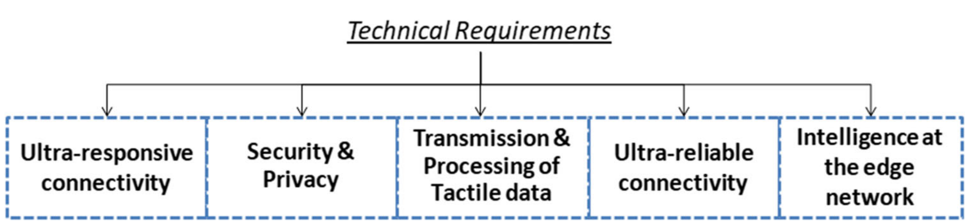


Fig. 7 Technical requirements



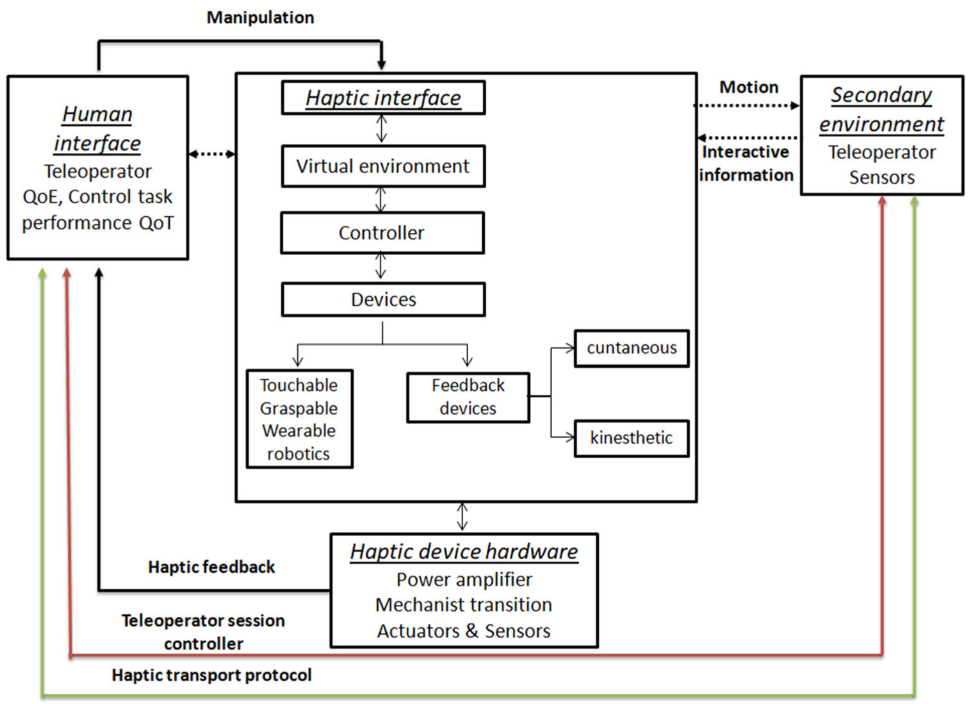


Fig. 8 Haptic data communication domains

low-latency communication [73]. Such mechanisms allow users to send and receive sensations of similar form in the virtual environment. Haptic communication is “interweaved” with haptic and non-haptic controls, programmed to allow the transmission of sensations thanks to feedback (“forced” feedback). The first category is related to the position, torque, speed, force, and displacement information of objects, whereas the second gives us friction percentage and texture of surface information [74, 75].

In a haptic system, the data transmission is categorized into three domains, as seen in Fig. 8. In the primary domain, the human body’s actions and movements produce and transfer haptic data via Human System Interface (HSI), in the controlled domain and data control by a teleoperator as a form of Telepresence and Teleaction (TPTA). This whole process is achieved through the network domain [76, 77].

Due to haptic data sensitivity, data transfer protocols in a haptic system are significant for the application of reliable techniques, developed to avoid any kind of errors and to ensure successful implementation of necessary constraints and qualitative features. Table 3 lists relevant protocols used in real-time conditions [78, 79].

3.2.3 Basic architecture of TIoT

To establish a fully functional network, end-to-end connectivity is a necessary design that provides reliability and security for direct and efficient communications related to the required operations via haptic and non-haptic controls. The basic TI architecture consists of three components. A primary domain, a network domain, and a secondary domain perform the interconnection of the layers through every stage of internal communication and data transmission. An example of a basic architectural model can be seen in Fig. 9.

The primary domain includes a human-system interface (HSI), a haptic robotic system that permits users to send and receive the sensations in real-time to a human operator. The input sensation is received and converted into suitable tactile coding, which then directs and controls the operations of the secondary domain. However, there is a limitation in the functionality of the robotic system. To optimize ultra-response and ultra-reliability, the TI should increase the Degree of Freedom (DoF) [80].

The next component of the architecture is the Network domain, designed kinesthetically for two-way communication between the primary and the secondary domain. This requires ultra-reliable, ultra-responsive, and secure connectivity for real-time data exchange, which is achieved with the contribution of 5G communication architecture based on cloud-aligned and service-based architectures. The core network (CN) and the radio access network (RAN) are the main components of the 5G communication architecture to satisfy TI’s essential requirements [81]. The network domain of the TI architecture includes the following:

- A router to transmit audio, video, and tactile information [82]
- Essential support for Network Functions of the 5G Service-based Architecture (SBA), such as the User Plane Function (UPF) which is vital for data transmission at the user

Table 3 Transport Protocols in a haptic system

Transport protocols	Functionality	Weaknesses/limitations
Transmition Control Protocol (TCP)	Packets reception Congestion control	Retransmission mechanism and congestion control algorithms, Drive the jitter values above the acceptable threshold for real-time services
User Datagram Protocol (UDP)	Manages to maintain a constant flow rate by minimizing jitter	Unreliable and connectionless mechanism. In case of congestion, it does not guarantee data packet delivery or rate adjustments
Real-Time Transport Protocol (RTP)	Carries interactive flow information between two-end systems Flow control and packet retransmission provision	It does not guarantee Quality-of-Service (QoS) It lacks retransmission capabilities
Real-Time Control Protocol (RTCP)	Jitter estimation. Information about the highest sequence number received Carries RTP statistical and data control Fraction of packets. Lost and cumulative number of packets lost	Heavily dependent on RTP for proper functionality
Real-Time Network Protocol (RTNP)	Time delay elimination caused by the corresponding multitasking operating system Network time delay reduction	Heavily dependent on specific operating systems e.g., UNIX
Synchronous Collaboration Transport Protocol (SCTP)	Reliable packet delivery of key updates Using scalable and fast IP multicast Attempts to deal with jitter by employing a buffer at the receiver Handling packets according to a timestamp	Unreliable delivery of normal updates Increased overall latency in the communication system Fixed delay for all messages
Network Adaptive Flow Control Algorithm for Haptic (NAFCAH)	Users can adjust its sensitivity according to the network variations of the internet connection and the significant haptic events Decreases its transmission rate in stages and it monitors congestion based on roundtrip time measurements	Not providing an accurate estimation of the (one-way) delay on the forward channel Cuts its transmission rate in stages once congestion is detected
Dynamic Packetization Module (DPM)	For telehaptic applications operating over shared networks. Enables network buffering for quick flush Minimizing the possibility of QoS violations. Estimates the delay on the forward and backward channels separately	Multiple DPM streams coexisting on a network would share the available bandwidth

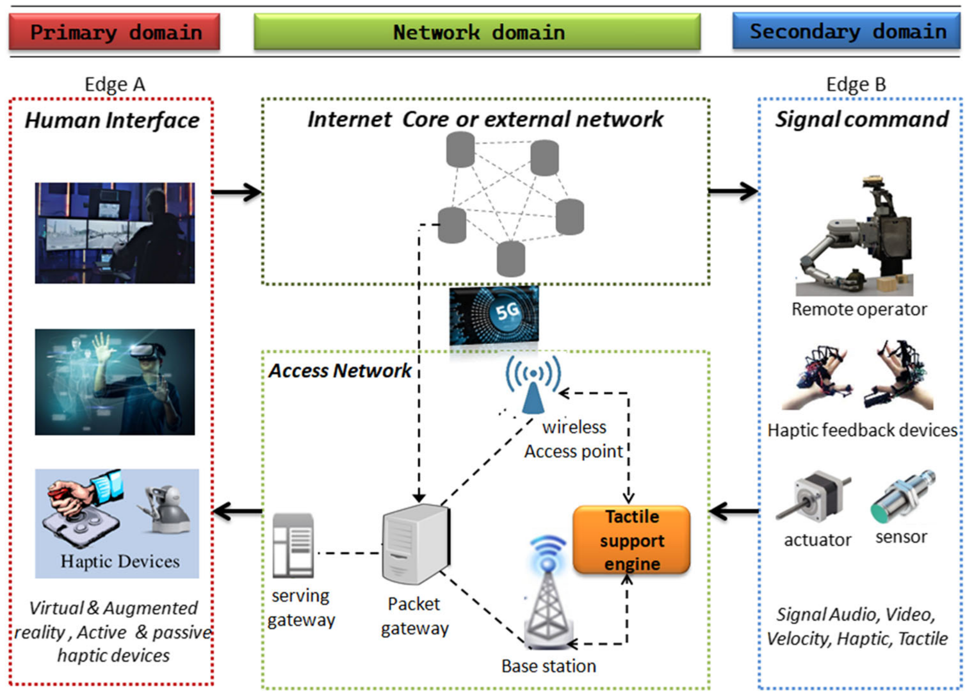


Fig. 9 Basic architecture of the tactile internet

level [83], and the Session Management Function (SMF) responsible for the interaction with the involved decoupled data plane and managing the session context of the UPF [84].

- The network slicing functionality, which facilitates the introduction of new services [83], provides optimization of network utilization by serving several types of communication through different slice practices, and while supporting them on a common infrastructure [85]
- A base station that connects wireless devices to the network through an antenna with radio communication. The area under coverage is called a cell, with a Tactile support system utilizing A.I. algorithms [86].

The third part of this architecture is the secondary domain which consists of a teleoperator that interacts with remote objects via controlled smart devices. This domain is operated either directly or through the operator, with control signals that are passed into the primary domain [87]. In this domain, there is two-way communication due to routers and gateways. The haptic input signals are transmitted from the primary through routers, switches, gateways, base stations, access points, and the tactile support engine, reaching the secondary section. As a result, various information is shared and exchanged through management or feedback signals, and Software-defined networking (SDN) [88].

The difference between conventional and tactile Internet is notable. The former is a medium for audio and visual transmission, whereas TI transfers the sensation of human touch in real-time [16]. The key distinction between haptic and non-haptic control is that in the first case, there is audio, visual, and haptic feedback from the system, whereas in the second case the feedback can only be audio and/or visual, with the notion of a control loop being absent.

3.3 Comparison of IoT and TIoT

Considering the development and emergence of TIoT, it is expected to present similarities with traditional IoT systems. However, there are significant differences defined by devices, connectivity, data processing, communication protocols, cloud, scalability, control process, human interactions, and upcoming challenges [89].

IoT devices utilize sensors and actuators connected to the physical components for the process of data transmission, whereas TIoT also includes Teleoperators. Connectivity is achieved through Ethernet, WiFi, NB-IoT, and NR, with a significant focus on TI due to the higher demands on constant network support for real-time tasks. IoT data processing and communication protocols process bursts of data for aggregation, storage, and management, whereas in the TIoT, there is constant data flow. Cloud in the IoT is utilized for data processing and models such as Infrastructure as a Service (IaaS) or Platform as a Service (PaaS), while it is not supported by TI due to the real-time data transmission [90]. Moreover, an increased number of connected devices can cause significant challenges for both technologies. IoT systems attempt to maintain, scalability, connectivity, and proper access control

Table 4 The main differences between IoT and TIoT

Features	IoT	TIoT
Devices	Devices, Sensors/Actuators,	Sensors, Actuators, Teleoperators (Human, Machine)
Connectivity	Not real-time Ethernet, WiFi, NB-IoT, LTE-M	Real-time (reaction time 1–10 ms), restricting connectivity to 5G networks
Data processing and Communication protocol	Bursts of data that can be aggregated, processed, and stored for automation purposes	Constant data flow in real-time
Cloud	IaaS (Infrastructure as a Service) or PaaS (Platform as a Service)	Not supported
Scalability	Large scale deployment	Near future large-scale deployment
Control process	Automated	Interactive
Human interaction	Remote monitoring and management	Remote control (human to robot)
Challenges	Security, scalability, connectivity and access control	Ultra-low latency of data packet round trip, high reliability, connection availability, safety, and security

[91]. Similarly, TIoT focuses on the ultra-low latency of data packet round trips, high reliability, connection availability and constant security of TI applications.

5G and beyond schemes constitute a promising solution for the challenges mentioned above. The main differences between IoT and TIoT are related to user interaction since TIoT is defined as a human-centric technology complementing human actions and activities [70].

Table 4 presents a summative list of the corresponding differences. Studying Table 4, we observe a respectable number of similarities between IoT and TI, combined with 5G networks. However, there are important differences in the perception of human interaction. Overall, TI technology embodies an anthropocentric model that increases the range of human capabilities, involved help of modern and automated devices [71].

4 5G-enabled applications and security of TIoT and metaverse

By correlating the intersection of the physical and virtual worlds, it is understood that there is a vast increase in related and available application fields. Several studies address the nature of such applications, mainly in terms of technological and hardware requirements [92]. However, both Metaverse and TIoT can be applied in several fields of daily life activities and transactions. Generally, audiovisual education is a significant case of application field, providing extraordinary benefits to users, with virtual tours of museums and archaeological sites being a relative example, among other studies [93–96]. TI availability enhances the VR and AR features of the corresponding applications, such as visual enhancement, content creation, interactivity, geolocation, portability and wearability, user and technical support, environment and familiarity. [18, 97, 98].

The gaming industry surpasses the typical entertainment purposes, by developing and designing applications that can improve the user's perception [99] e.g., critical thinking [100], education and knowledge [101], and advisory mindset [102].

The experience of remote working and telecommuting is also enhanced by TIoT and Metaverse. Companies gradually implement an immersive concept called "offline", where the sounds of the company's main working space are transmitted to the remote worker's environment, providing the feeling of being on-site. Metaverse is mainly defined by its socialization, with applications allowing users to create their own personal avatars, customizing their features and appearance, and subconsciously eliminating social discrimination [103, 104].

Trading and marketing are two unprecedented fields for Metaverse users since each platform utilizes a common, accepted, and unified virtual currency for commercial purposes. Moreover, advertisement related to the corresponding commercial field is more attractive due to their vividness and immersion. Finally, regarding healthcare applications, telemedicine utilizes Information Technologies (IT), combined with wireless communication, audiovisual data, and haptic feedback [105–107].

In Fig. 10, we present two lists of applications, as an aspect of the 5G and beyond TIoT, respectively, as they are reflected in the Metaverse platform.

The safety and security of automated systems are perhaps the most important aspects of consideration, both for developers and users. Requirements for sufficient and secure mechanisms increase, due to the availability of sensitive smart devices. In the case of the Metaverse, such sensitivity can be found in the components structuring its virtual environment, including network technologies such as TIoT, 5G networks, and beyond [108].

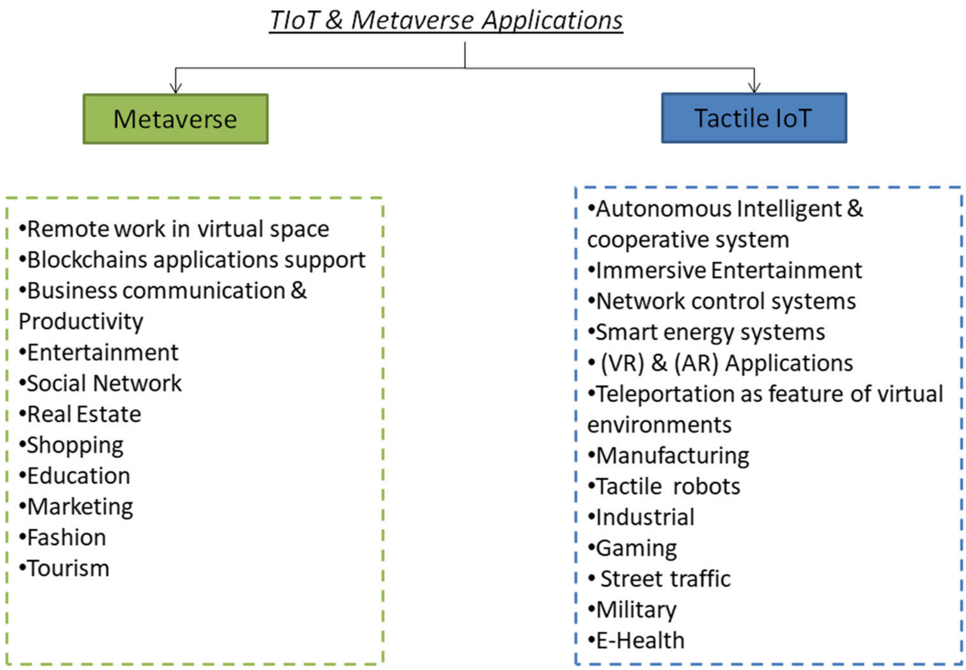


Fig. 10 Applications of TIoT and Metaverse

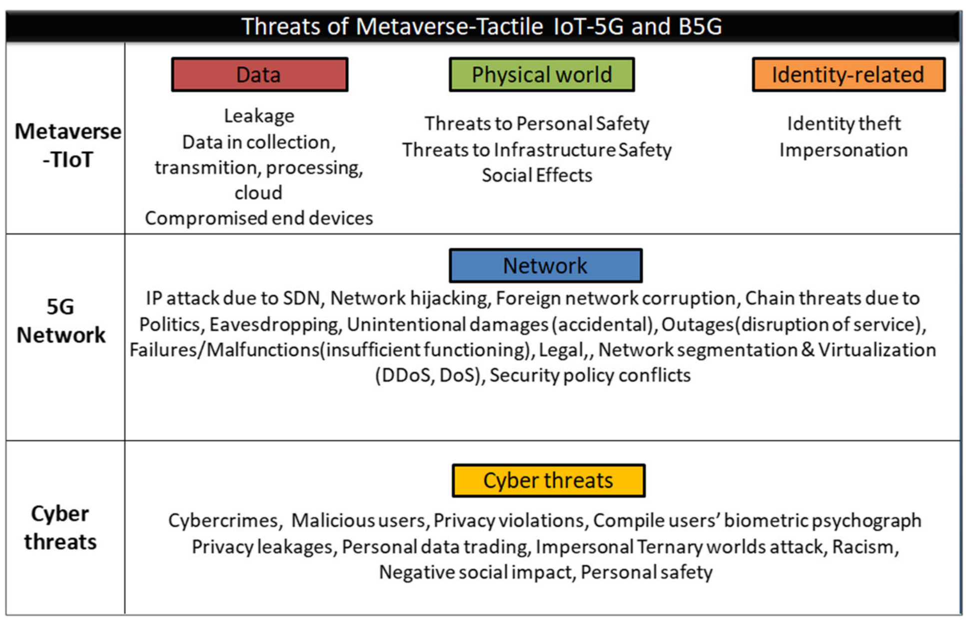


Fig. 11 TIoT, Metaverse and 5G and beyond networks threats

Proper management of users' identity and theft protection are highly required, since avatars, digital assets, social relationships, and an individual's digital life in general can be compromised [109]. Such malicious attacks cause unnecessary data and information congestion, resulting in high latency [110].

Data collected through mobile devices or avatars are exposed to falsification, forgery, replacement, and elimination of unprocessed data, causing false information to be spread [111] and misleading Metaverse systems [112]. Metaverse is also considered an extension of Cyber-Physical and Social Systems (CPSS), with physical systems, human society, and cyber systems being interconnected through complex interactions [113]. Virtual world threats are capable of affecting physical infrastructures, personal safety, and the integrity of human society. Corresponding examples are privacy infiltration through malicious attacks on personal wearable devices or indoor sensory systems [114], detecting weak entry points of the infrastructure's security [115], user addiction [116], rumor prevention [117] child pornography, biased outcomes, extortion, cyberbullying [118], even simulated terrorist camps [119].

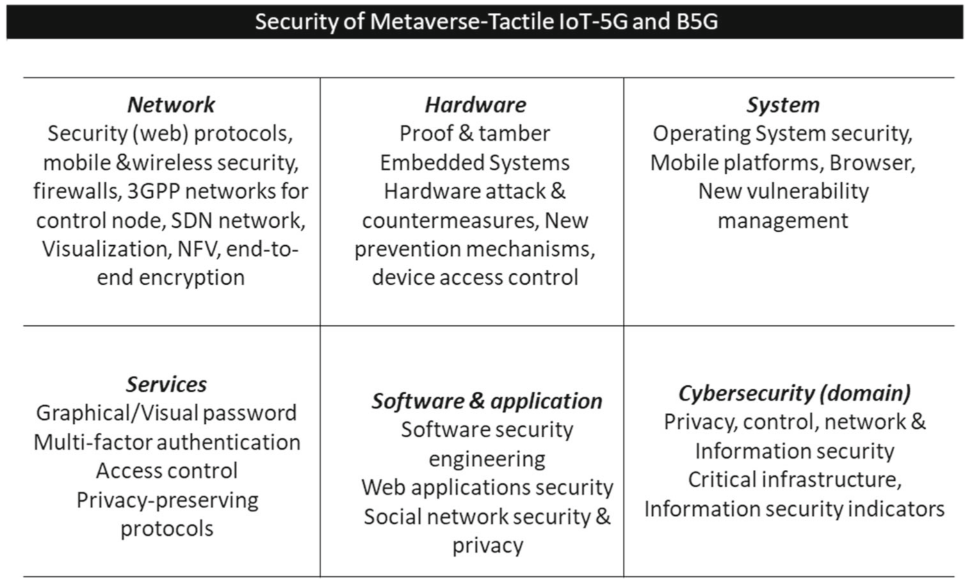


Fig. 12 Security mechanisms for TIoT, Metaverse and 5G and beyond threats

Due to the wireless technologies implemented into Metaverse infrastructure, its network is susceptible to malfunction in terms of unexpected disruption of service and availability [120, 121]. Such attacks are related to insufficient functionality, eavesdropping, device damages, disabling or gaining unauthorized access to physical assets [122–125], e.g., Denial of Service (DoS), Distributed Denial of Service (DDoS), Man in the Middle (MITM), and ransomware [126].

Both TIoT and Metaverse share foundational requirements regarding security and privacy, such as confidentiality, authentication, central management, identity management, processing of duplicated data, user privacy, and advanced security mechanisms focusing on enhanced communication protocols, and encrypted firewalls [127]. Prevention strategies include updated security mechanisms of devices, constant password updates, defense mechanisms for radio jamming, control and data channel attacks [4].

In Fig. 11, we present examples of relative security threats and continue with suggested security solutions in Fig. 12.

5 Advantages, limitations, and challenges of 5G, TIoT, and metaverse

TIoT and Metaverse benefits can be considered human-centric and infused with 5G networks can be categorized as technological, economic, and social. By studying the definitions and capabilities of these technologies, on a theoretical level, we are referring to perfect unblemished environments, not defined by socioeconomic status regarding connection, allowing users to interact and behave as in everyday life.

Regarding their limitations, they can be considered as the basis of existing challenges, related to their improvements and further evolution. Initially, the existence of such technology is heavily dependent on the user's interest in virtual interactions, as well as the overall user activity. Currently, there are no available data ensuring the sustainability of such technologies. Another important limitation concerns the maintenance of continuous user connectivity. Network and hardware components are not technologically complete regarding the corresponding requirements, although the next generation of 5G and beyond networks promise ultra-low power consumption, ultra-security and reliability, autonomy, and scalability, high speed and high capacity, low latency, and simultaneous connections. In terms of hardware and software components, the simulation of the physical world is partially achieved through sensors, since human senses such as smell or sense of the wind are not possible. Furthermore, regarding the behavior and expression of humans, it is known that they act differently depending on space–time, while in these technologies user's behavior is based solely on the individual's personality regarding reaction time during virtual interactions.

Table 5 lists the advantages and limitations of these technologies, categorizing them according to 5G and beyond technologies, and the Metaverse which is enabled by the combination of 5G and TIoT.

Metaverse as technology continues to be a significant research topic, raising questions regarding its structure and development, but also additional challenges. These challenges can be classified into technical, interactive, security, both in terms of user privacy and data integrity, ethical, as well as user-related challenges e.g., mental and emotional. It is noticed that the corresponding types of challenges are interconnected and complement each other. Especially from a technical point of view, the main rising challenge is the

Table 5 Advantages and Limitations of 5G and beyond and Metaverse

Technology	Advantages	Limitations
5G and beyond	High Resolution	Radio signal issues
	Collection technologies, all networks on one platform	Mobile Network integration difficulties
	More effective and efficient	Security and Privacy
	Capable of broadcasting data in a wide range	Technology is still researched and under development
	Supports heterogeneous services (and private networks)	Heterogenous services unable to be supported by Legacy Devices
	Multiple simultaneous services	High cost (new devices, infrastructure development)
	Visualizing the universe, galaxies, and detecting natural disasters	Additional risks from network slicing and virtualization
	Extreme broadband and large capacity	Interrupted connections due to incomplete technology
	Ultra-security and resiliency	Lack of physical senses (sunlight, air, smell)
	Ultra connectivity	High latency and restricted available storage
	Enhancing creativity and Imagination	Minimum available resources
TIoT	Ultra-low latency with a combination of high availability, reliability, and security	Fiber connection speeds can reach 200 km/s, while TIoT requires ranges of at least 200 km
	Enables real-time interaction between humans and machines	High latency in terms of communication due to excessive data flow
	Provides visual feedback	Current network infrastructures are not compatible with the corresponding feature
	Requires 1 ms end-to-end latency and a system response of 1 ms for diversity applications	Existing network infrastructures are conceptually and technically insufficient to support emerging TI applications
Metaverse	Technological literacy and skills, education for all	Manual operations are not enough to ensure security
	New career opportunities	Sustainability
	Opportunities for self-expression	Distributed edge clouds are susceptible to new attack forms
	Real-time experiences, additional gaming entertainment, Monetization	Insufficient maintained security and quality
	Medical treatments	Additional security requirements in terms of connectivity to avoid issues in applications such as telemedicine

development of a solid 5G network architecture, ensuring confidentiality, and creating models that assist the proper functionality of its features [92].

Metaverse is connected directly to the physical world, implying that users' virtual identities are genuine. As a result, there is a clear urgency for new network generation to provide data security and guarantying user privacy [128, 129].

Unlike previous network generations, 5G promises higher data transmission rates and steady connectivity, though the technology responsible for these features is still under development [130, 131]. The complexity and diversity that

Table 6 Challenges of TIoT and Metaverse

Field	Challenges
Technical	Stable 5G-IoT architecture Scalability and heterogeneous network management Interoperability Ensuring security and privacy Wireless Software-Defined Network (SDN) D2D communication Identity Management Lack of standards TI communication speed Sensing and geomatic capabilities of TI haptic devices
Privacy	Creating multiple user avatars. Introducing Federated Learning to secure local data Harmful content Lack of Metaverse content Security, Safety, and Privacy (SSP). Intellectual Properties Verification of digital assets ownership
Recourse allocation	Leveraging shared technology Developing appropriate model training solutions through edge nodes Limited resources Sufficient energy sources for data center functionality
Delay	Auction mechanism based on deep learning to improve communication efficiency Blockchain-based incentive mechanism
Communication	Network slicing Compatible Internet protocols Short-range communications Dielectric materials used in fabricating sensors, power consumption, visual fidelity
Interaction	AR and VR technologies High-quality and high-performance models that can support proper retina display and pixel density for a realistic virtual immersion Interconnection of different virtual worlds Interoperability Democratic usage
Finance	Cryptocurrency and unregulated payment Availability of various cryptocurrencies
Emotional and mental impact	Mental issues Depression, stress, and anxiety Toxic social worlds Antisocial behavior Cyberbullying and harassment
Ethical beliefs	Social norms and an overseeing decentralized body Ensuring security and upholding privacy National or international interest conflicts, and proper legislation

define it, require the creation of a sufficient ecosystem, with increased computational power, significant data transmission, and storage, while supporting the essential prerequisites of a new digital economy and assisting the rising demands of the Metaverse [47, 132].

Regarding communication and user interactivity, Extended Reality (XR) technologies, which is a combination of VR, AR, and Mixed Reality, require further development for the creation of lightweight wearable, portable, and transparent devices, in order to provide a highly immersive user experience at a low cost [105, 133]. Moreover, proper transaction management and cryptocurrency availability are required, since they are considered some of the most popular Metaverse features [47].

Finally, additional challenges are rising regarding the emotional and mental impact on users, as well as cases of false information and copyright infringement [133]. Metaverse should implement ethical norms, requiring the development of mandatory rules of conduct and enforcement of necessary penalties, while focusing on the availability of a safe and healthy environment [134–136].

Table 6 presents a comprehensive list of the corresponding challenges associated with the Metaverse and TIoT.

6 Conclusion

In this article, we discussed the concepts of the TI, 5G and beyond communication networks, and their potential as KET for the future Metaverse. In particular, we analyzed the foundations of these technologies, their operating frameworks, and their anticipated outcomes. The corresponding technologies are related and directly interconnected through a universal platform connecting the natural and the virtual world, where each user has the opportunity to experience a virtual resemblance to real life. Although the supported technologies are still in their infancy, the first steps have been initiated.

Currently, Metaverse is considered a state-of-the-art technology with a variety of experimental platforms, while promoting the development of wearable and portable devices, upgraded with 5G connectivity, that provide a highly immersive experience, both remotely and in real-time through haptic devices and TI. Since such devices are supported by 5G networks, requirements such as low latency, reliability, increased data rate, and overall efficiency, are constantly rising. However, 5G and beyond networks are still considered an emerging field, while indicating several technical gaps and the need for additional research. Generally, the interconnection of different types of systems raises several questions regarding data safety, privacy, and integrity, due to the constant information flow.

Regarding the combination of Metaverse, TIoT, and 5G and beyond systems, it is concluded that existing infrastructures are not capable of supporting the corresponding features of each technology. Similarly, haptic devices responsible for the transmission of senses are limited in terms of Degrees of Freedom (DoF), due to the restricted available technology. However, it is expected that 5G will be able to support a wide range of TI applications with additional physical senses and diverse QoS requirements, with system optimization being the primary goal. Finally, the combination of the corresponding technologies with AI and smart mechanisms has the potential for total technological revolution in modern society.

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Declarations

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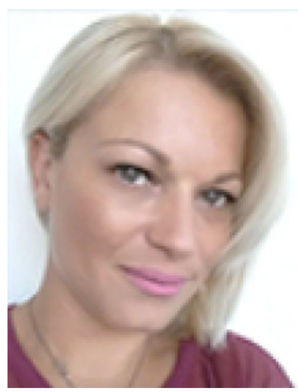

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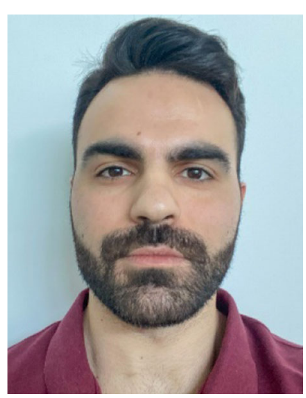

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