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Review

Smart Manufacturing and Tactile Internet Based on 5G in Industry 4.0: Challenges, Applications and New Trends

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Abstract: For many applications deployed in manufacturing networks, communication latency has been a significant barrier. Despite the constant development of improved communication protocols and standards during Industry 4.0, the latency problem persists, lowering quality of services (QoS) and quality of experience (QoE). Tactile internet (TI), with its high availability, security, and ultra-low latency, will add a new dimension to human-machine interaction (HMI) by enabling haptic and tactile sensations. The tactile internet (TI) is a cutting-edge technology that uses 5G and beyond (B5G) communications to enable real-time interaction of haptic data over the internet between tactile ends. This emerging TI technology is regarded as the next evolutionary step for the Internet of Things (IoT) and is expected to bring about massive changes towards Society 5.0 and to address complex issues in current society. To that end, the 5G mobile communication systems will support the TI at the wireless edge. As a result, TI can be used as a backbone for delay mitigation in conjunction with 5G networks, allowing for ultra-reliable low latency applications like Smart Manufacturing, virtual reality, and augmented reality. Consequently, the purpose of this paper is to present the current state of 5G and TI, as well as the challenges and future trends for 5G networks beyond 2021, as well as a conceptual framework for integrating 5G and TI into existing industrial case studies, with a focus on the design aspects and layers of TI, such as the master, network, and slave layers. Finally, the key publications focused on the key enabling technologies of TI are summarized and the beyond 5G era towards Society 5.0 based on cyber-physical systems is discussed.

Keywords: tactile internet; Smart Manufacturing; 5G; Industry 4.0; Society 5.0

Citation: Mourtzis, D.; Angelopoulos, J.; Panopoulos, N. Smart Manufacturing and Tactile Internet Based on 5G in Industry 4.0: Challenges, Applications and New Trends. *Electronics* **2021**, *10*, 3175. https://doi.org/10.3390/electronics10243175

Academic Editor: George A. Tsihrintzis

Received: 11 November 2021
Accepted: 16 December 2021
Published: 20 December 2021

1. Introduction

1.1. Evolution of Network Technologies

Over the last decade, the manufacturing industry has been undergoing a digital transformation known as "Industry 4.0". Cloud, artificial intelligence (AI) and machine learning, new connectivity technologies (5G, Wi-Fi 6, etc.), Internet of Things (IoT) and sensor technology, digital twins, and robotics are all contributing to the digitization of manufacturing [1]. Most manufacturers strive to increase efficiency and productivity. Most businesses aim for a 3% increase in productivity year over year. Thus, operational equipment effectiveness (OEE) is an important performance metric that assesses the efficiency of a production line by weighing three factors to produce an overall score: availability, performance, and quality. Additionally, three important challenges that manufacturers are facing in the volatile global marketplace are summarized as follows:

- Global competition: as revenues from the traditional model of selling products are squeezed, manufacturers must find ways to become more efficient on a continuous basis in order to compete at lower prices or adopt new business models.
- New consumer trends: consumers are increasingly expecting "on-demand" products that are fully customizable, putting pressure on manufacturers to reduce cycle times and create unique products while maintaining efficiencies.

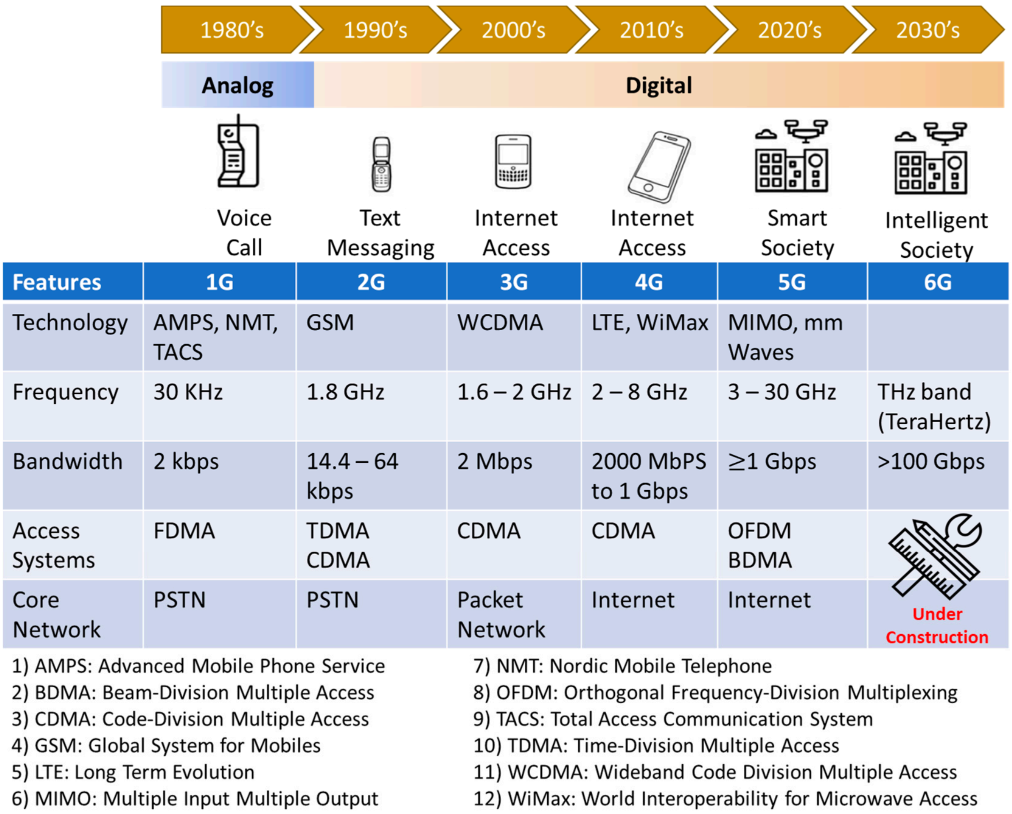
- Skills shortages in the workforce: the introduction of new technologies necessitates the acquisition of new skills, and the manufacturing industry is struggling to attract new talent, with an estimated 2.4 million unfilled positions (or 15% of the total workforce) in the US alone by 2028 [2].

Improving efficiency is the key to addressing the challenges. To that end, technology will be a key driver by enabling rapid digital transformation. Data can help make better decisions, but the real benefits will come from developing new business and operating models. The four pillar technologies that will help in driving efficiency are big data, analytics, connectivity and management [3].

While most people agree that better use of data can lead to better decision-making, there are still barriers to overcome. Manufacturers, for example, are facing interoperability issues. By extension, this issue is caused by the lack of tools and methods for easily connecting machines, tools and plants, and, most importantly, to aggregate data across silos in a consistent manner. On the other hand, a new generation of mobile communications is realized approximately every ten (10) years, as is illustrated in Figure 1. More details for the evolution of network technologies is listed hereafter [4,5]:

- 1G–voice call: the 1G mobile network was put into use in the early 1980s. It has voice communication and limited data transmission capabilities.
- 2G–message passing: in the 1990s, the 2G mobile network improved voice quality, data security, and data capacity and provided limited data capabilities through the use of GSM (global system for mobile communications) standard circuit switching.
- 3G–multimedia, text, internet: the first commercial 3G service was introduced in 2003, including mobile internet access, fixed wireless access, and video calling.
- 4G–real-time data, car navigation, video sharing: 4G was launched in 2008, making full use of all IP networking and relying entirely on packet switching. Its data transmission speed is 10× compared with 3G network.
- 5G–is the most recent generation of mobile technology, and it differs from previous generations in that it is not simply a speed increase over 4G. It is more flexible than previous generations of cellular technology because it is software-based. Customers will be able to use different characteristics of 5G tailored to meet the requirements of specific applications, rather than one network that fits all.
- 6G–is the next generation of mobile technology also known as "Next G", which is still under development. Currently, initiatives are starting to form and research projects are set up in an attempt to begin the design, development, and experimentation on the required network infrastructure to support this new mobile network generation. According to recent research [6], China has already set up two working works. Similarly, Japan has also invested $2 billion (two billion US dollars) in order to support research activities for 6G. Europe has also approved the research of 6G under the Horizon 2020 plan. North America has also begun working on the initiative called "Next G", mainly at a university level.

Users can share data on the go with their smart devices using mobile communication and the mobile internet (MI). MI has millions of connected smart devices and has revolutionized various industries such as logistics, education, healthcare, and transportation in order to maintain quality of service (QoS) and quality of experience (QoE) for diverse customers [7]. It also enables device-to-device (D2D) communication and invented the term "Internet of Things" (IoT), which allows low-power devices and/or equipment to execute specific functions in the area in which they are installed [8]. Mobile devices can share prime or vital information in situations when a millisecond delay could harm a human life via D2D communication. The current cellular network architecture is not adequate for such sensitive data sharing, which has a latency of more than 20 milliseconds, due to poor data rates and significant delays.



Features	1G	2G	3G	4G	5G	6G
Technology	AMPS, NMT, TACS	GSM	WCDMA	LTE, WiMax	MIMO, mm Waves	
Frequency	30 KHz	1.8 GHz	1.6 – 2 GHz	2 – 8 GHz	3 – 30 GHz	THz band (TeraHertz)
Bandwidth	2 kbps	14.4 – 64 kbps	2 Mbps	2000 MbPS to 1 Gbps	≥1 Gbps	>100 Gbps
Access Systems	FDMA	TDMA CDMA	CDMA	CDMA	OFDM BDMA	Under Construction
Core Network	PSTN	PSTN	Packet Network	Internet	Internet	

1) AMPS: Advanced Mobile Phone Service
2) BDMA: Beam-Division Multiple Access
3) CDMA: Code-Division Multiple Access
4) GSM: Global System for Mobiles
5) LTE: Long Term Evolution
6) MIMO: Multiple Input Multiple Output
7) NMT: Nordic Mobile Telephone
8) OFDM: Orthogonal Frequency-Division Multiplexing
9) TACS: Total Access Communication System
10) TDMA: Time-Division Multiple Access
11) WCDMA: Wideband Code Division Multiple Access
12) WiMax: World Interoperability for Microwave Access

Figure 1. Evolution of mobile network technologies.

However, for most smart applications, this delay for D2D connections is excessively long. Similarly, the term "tactile internet" (TI) was coined in early 2014 to characterize the ability to monitor and, as a result, act over the internet [9]. As a result, TI is expected to offer up several new opportunities and applications that will improve the quality of life and work. According to market research, the worldwide market might be worth up to $20 trillion, accounting for at least 20% of global GDP today [10]. Even though the term Internet of Things was established in 1995 it has recently faced significant popularity. Moving on, the TI is considered to be the evolution of IoT. Hereinafter, the key characteristics of each internet era are summarized [11]:

- Mobile internet: suited for static or streaming content, video with limited resolution, web browsing
- Internet of Things (IoT): machine-to-machine (M2M) communication, billions of inter-connected smart devices, low rate, latency, secure and reliable
- Tactile internet: human-to-machine communication (H2M), ultra-low latency, ultra-high availability, end-to-end security

1.2. Vision of Tactile Internet

The International Telecommunication Union (ITU-R) initiated a program in early 2012 to establish "International Mobile Telecommunication (IMT) for 2020 and Beyond", laying the way for 5G research activities around the world. Figure 2 [12] illustrates the 5G Roadmap. The International Telecommunications Union (ITU) has a long history of producing radio interface standards for mobile communications. IMT-2000 and IMT-Advanced are part of the International Mobile Telecommunications (IMT) framework of standards, which encompasses 3G and 4G industry perspectives and will continue to evolve as 5G with IMT-2020. The ITU multi-stakeholder framework's reliability ensures a positive outcome for the global telecommunications community.

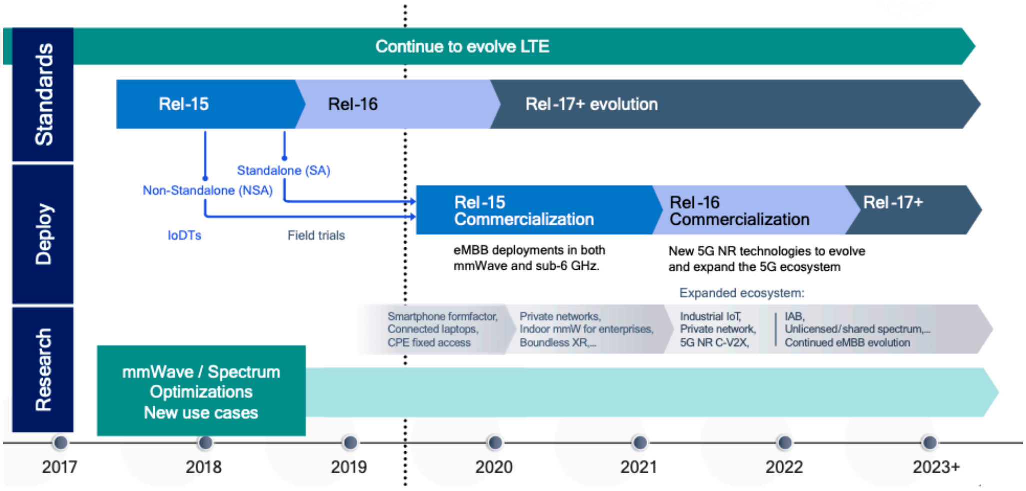


Figure 2. 5G Roadmap of IMT 2020 [12].

The TI, according to one ITU-T Technology Watch Report [13], has taken a quantum leap forward. Tactile and haptic sensations will be enabled by TI's high availability and security, ultra-fast reaction times, and carrier-grade reliability, adding new dimensions to human-machine contact (HMI) [14]. The 5G technology vision envisions 1000-fold increases in area capacity, 10 Gb/s peak data rates, and connections for at least 100 billion devices to achieve this goal. The main challenge of 5G wireless access and core network architectures is to enable new machine-centric use cases that are currently unsupported by cellular networks. Additionally, the TI is characterized by the following technological capabilities [12]:

- Ultra-low latency; 1 ms and below latency (as in round-trip-time/round-trip delay)
- Ultra-high availability; 99.999% availability
- Ultra-secure end-to-end (E2E) communications
- Persistent very high bandwidth capability (>1 Gbps)
- Bandwidth: data rates of 100 MB/s on average
- Capacity: up to 1 million devices per square kilometer
- Reliability: 99.999% network reliability
- Mobility: Seamless transfer between radio nodes up to 500 km/h
- Battery Life: up to ten (10) years battery life for low power (IoT) devices

However, it has to be mentioned that the TI should be able to highlight the difference between humans and machines. This should be used in situations where there is a high demand for machines and little interference from humans. Machines should be used to supplement humans rather than to replace them [15].

1.3. Challenges and Motivation-Existing Cellular Technologies Cannot Support Tactile Internet Yet

Tactile applications based on control communications can now be developed with 1 ms round-trip latency (RTL) and ultra-high reliability and availability (as envisioned for 5G). As such, for the global economy, the TI has the potential to be a game-changer. Table 1 compares the industrial automation performance requirements for 5G. To that end, the purpose of this study is to look into how 5G can fuel Smart Manufacturing and TI by reviewing existing trends, difficulties, and future trends. There will also be a discussion of the potential ramifications for operators in terms of network infrastructure and commercial prospects. The rate 10× factor [16] is fast increasing the data rate need in IoT.

As already mentioned, the critical challenge is to achieve a tolerable RTT of 1 ms in order to facilitate TI-related services and applications. Nonetheless, there are numerous challenging solutions for reducing network RTT. As a result, another motivation of the paper is to adopt TI technology in order to incorporate technological advancements such as software defined networking (SDN), network function virtualization (NFV), network coding, physical MAC-layer protocols, and cloud networking technologies that promise to meet the needs of the TI [17].

Table 1. Comparison of peak data rate versus latency [18].

Use Case		Availability	Cycle Time	Payload Size	Number of Devices	Typical Service Area
Motion control	Printing machine	>99.9999%	<2 ms	20 bytes	100	100 m × 100 m × 30 m
	Machine tool	>99.9999%	<0.5 ms	50 bytes	~20	15 m × 15 m × 15 m
	Packaging machine	>99.9999%	<1 ms	40 bytes	~50	10 m × 5 m × 3 m
Mobile robots	Cooperative motion control	>99.9999%	1 ms	40–250 bytes	100	<1 km^2
	Video-operated remote control	>99.9999%	10–100 ms	15–150 kbytes	100	<1 km^2
Mobile control panels with safety functions	Assembly robots or milling machines	>99.9999%	4–8 ms	40–250 bytes	4	10 m × 10 m
	Mobile cranes	>99.9999%	12 ms	40–250 bytes	2	40 m × 60 m
Process automation (process monitoring)		>99.99%	>50 ms	Varies	10,000 devices per km^2	

The present 4G network is incapable of handling such high data rates. In this context, 5G technology has the potential to lead IoT applications that require high data rates, such as smart cities, smart grids, smart healthcare, connected cars, and linked homes [19]. By 2020, there will be more than 50 billion gadgets connected to the internet.

Issues and concerns with IoT-based smart home applications, such as latency and reliability, were highlighted by Alaa et al. [20]. TI can be utilized to alleviate these difficulties because it has ultra-low latency and carrier-grade frequency. The problems of IoT will be addressed by a future technical development, a 5G-enabled TI. In addition, the following are the components of TI: (a) fixed internet [8], (b) mobile internet [21], (c) things internet [22], and (d) tactile internet [8].

The 5G technology will be integrated in a heterogeneous network infrastructure. Three major frequency bands have been made available for use of 5G in Europe. These three bands are 700 MHz, 3.6 GHz, and 26 GHz. Next, the CBRS (Citizens Broadband Radio Service) band, which operates at 3.5 GHz, was opened up for commercial use in the United States in January 2020. Wi-Fi networking is also getting a makeover, and this supplementary technology will contribute to the 5G ecosystem. Finally, the IEEE 802.11ax specification is referred to as Wi-Fi 6 by the Wi-Fi Alliance because it is the sixth generation of Wi-Fi. Similarly, following the ongoing standardization, a new IEEE P1918.X standard has been defined for the TI [23,24]. IEEE P1918.X describes the TI's architecture technology and assumptions, whereas IEEE P1918.X.1, IEEE P1918.X.2, and IEEE P1918.X.3 focus on codecs, AI, and MAC for the TI, respectively. Furthermore, significant effort has been expended to form a working group for low latency industrial IoT (IIoT) applications such as intelligent transportation systems, Industry 4.0, and Health 4.0 [25]. Finally, Figure 3 presents verticals sectors' capabilities and requirements spider charts [26].

In an attempt to properly introduce the key concepts of this research work, a short glossary is compiled below in the form of a table (refer to Table 2). Consequently, this table can facilitate the readership to become more familiar with the concepts of mobile networks, 5G, tactile internet, and Industry 4.0.

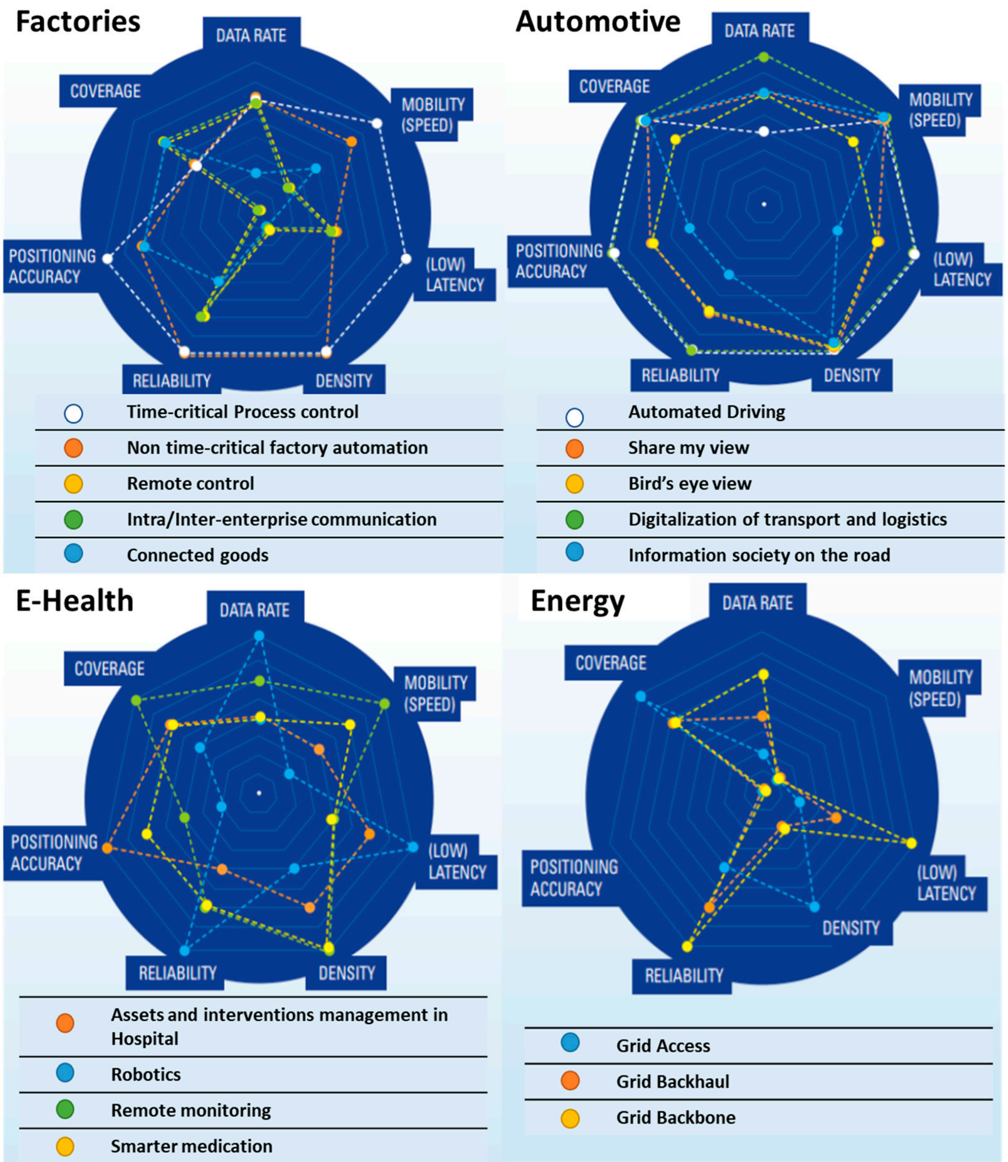


Figure 3. Verticals sectors' capabilities and requirements spider charts [26].

Table 2. Glossary of Key Concepts.

Term	Definition	Source
Internet of Things (IoT)	IoT can be realized as a new form of network created by physical devices. In this type of network, the physical devices are called things. Each thing is embedded with sensing systems and associated software which enable the connection and data exchange with other things over the internet.	[27]
Tactile internet (IT)	According to the International Telecommunication Union (ITU), TI can be realized as the next generation of internet network. This new generation of internet is based on the combination of ultra-low latency, extremely high network availability, reliability, and security. Ultimately, TI will enable the advanced human-machine interface (HMI), based on the interaction of humans with the new TI environment through human senses.	[13,28]
xG mobile network, $x \in [1,6]$	This notation refers to the mobile network generations, encapsulating the corresponding communication protocols. Concretely, "G" refers to "generation", whereas the numerical value refers to the number of the generation. For example, 5G refers to the fifth generation of mobile networks	[29]

Based on the abovementioned identified challenges, the contribution of this state-of-the-art paper can be summarized as follows:

1. It provides a state-of-the-art review on 5G and related key technologies under the framework of Industry 4.0 and beyond.
2. It identifies three important challenges faced by industrial stakeholders in the volatile global marketplace.
3. It highlights the fact that existing cellular technologies cannot support the tactile internet yet.
4. It clearly introduces the era beyond 5G. The well-known Figure 1 that presents the evolution of mobile network technologies has been elaborated and includes the main features of the 6G technology for the years to come.
5. It adds taxonomy of tactile internet ultra-low latency (URLL) manufacturing applications that will be boosted by 5G technology, such as the tactile internet and haptic feedback. Moreover, this state-of-the-art paper introduces education frameworks for up-skilling and re-skilling the next generation of engineers.
6. It integrates the concept of personalized healthcare under the concept of Society 5.0 and, more specifically, explains the progress of cyber-physical systems towards the realization of a super smart society 5.0.
7. Finally, the current paper extends the scope of the most recent comprehensive surveys on 5G and integrates the new developments of smart factories in Wi-Fi6 for industrial Internet of Things (IIoT) applications.

The remainder of the paper is structured as follows. In Section 2, the most pertinent literature on the topics of international goals for 5G beyond 2020, 5G usage scenarios, the potential, and the impact of 5G in manufacturing as well as the latency budget of a data life cycle in TI are presented. Next, in Section 3, use cases in the manufacturing industry enabled by 5G are discussed, and in Section 4 a generalized framework for TI in the beyond 5G era is provided. Furthermore, the integration of 5G and TI to industrial case studies is presented by the authors. Finally, in Section 6 the research work results are discussed, conclusions are drawn, and future research points are discussed.

2. State-of-the-Art

2.1. Review Methodology

For the purposes of this research, emphasis was placed on electronic academic papers and scientific articles, as well as numerous business reports indexed in globally recognized databases, such as Google Scholar and Scopus, as well as specific consulting and technology companies. The recently published papers were included in the process, from 2019 to 2021. The flowchart of the research methodology that was based on [7] is presented in Figure 4.

2.2. International Mobile Telecommunications (IMT) for 5G beyond 2020

By 2030 it is estimated that 5G technology will increase the global manufacturing gross domestic product (GDP) by 4%, which is equivalent to approximately $740 billion. This forecast is based on the new use cases and improvements in existing applications that 5G brings versus other technologies, as well as how these improvements will affect productivity (Figure 3) [12,30,31]. The evolution of mobile communications has significantly affected socio-technical evolution in recent decades, by contributing to the economic and social development of both developed and developing countries. Mobile communications have become deeply ingrained in all aspects of daily life. The evolution of mobile communications systems and socio-technical trends are expected to remain tightly coupled, forming a foundation for the next generation of society in 2020 and beyond. Therefore, new demands, such as increased traffic volume, a greater number of devices with varying service requirements, improved quality of user experience (QoE), and improved affordability through cost reduction, will necessitate a greater number of innovative solutions soon. In a research published by the International Mobile Telecommunications (IMT) [12], the potential user and application and technological trends, spectrum applications can be summarized to the following:

- Support very low latency and high reliability human-centric communication
- Support very low latency and high reliability machine-centric communication
- Support high user density
- Maintain high quality at high mobility
- Enhanced multimedia services
- Internet of Things (IoT)
- Convergence of applications
- Ultra-accurate positioning applications

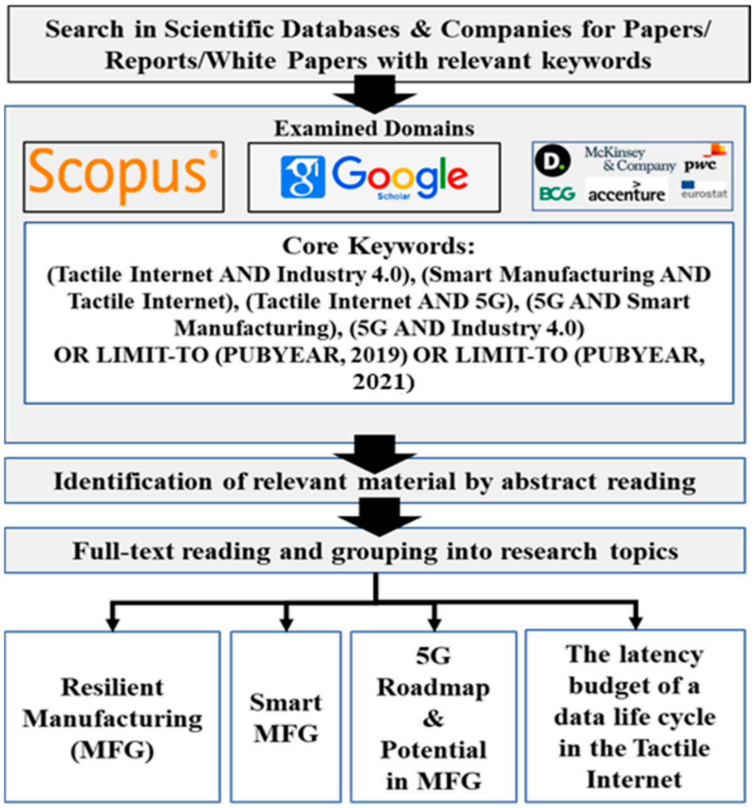


Figure 4. Research Methodology for Literature Review.

2.3. Spectrum for 5G Private and Dedicated Networks

Access to the appropriate radio spectrum is required for 5G industrial applications, which is a critical consideration for any wireless technology. Most mobile operators are relying on the spectrum in the 3.5 GHz range (3.3 GHz–4.2 GHz) to launch commercial networks. It is on its way to becoming a globally harmonized band for 5G, which will help bring network equipment and devices down in price. 5G, on the other hand, supports a much wider range of spectrum options, particularly across licensed frequency bands, which can accommodate a wider range of requirements. The spectrum ranges for 5G are illustrated in a comprehensive manner in Figure 5.

- Low frequency bands, e.g., under 1 GHz, supporting wide area coverage e.g., wide area logistics and sensor networks;
- Mid frequency bands, e.g., in the core 3.3 GHz to 3.8 GHz range, delivering expanded device capacity and bandwidth. It is expected that public mobile network operators will each have between 80 MHz and 100 MHz in prime 5G mid-bands;
- High frequency bands known as "millimeter wave", e.g., 26 GHz, 28 GHz and 40 GHz. This is of particular importance to streaming video, image/video processing, vir-

tual reality/augmented reality, and more general wireless networking for flexible production lines, AGVs, machine vision and supply chain management.

- Mobile network operators should have at least 1 GHz of spectrum available each in the high frequency bands, enabling those industrial use cases which demand peak 'traffic volume density'.

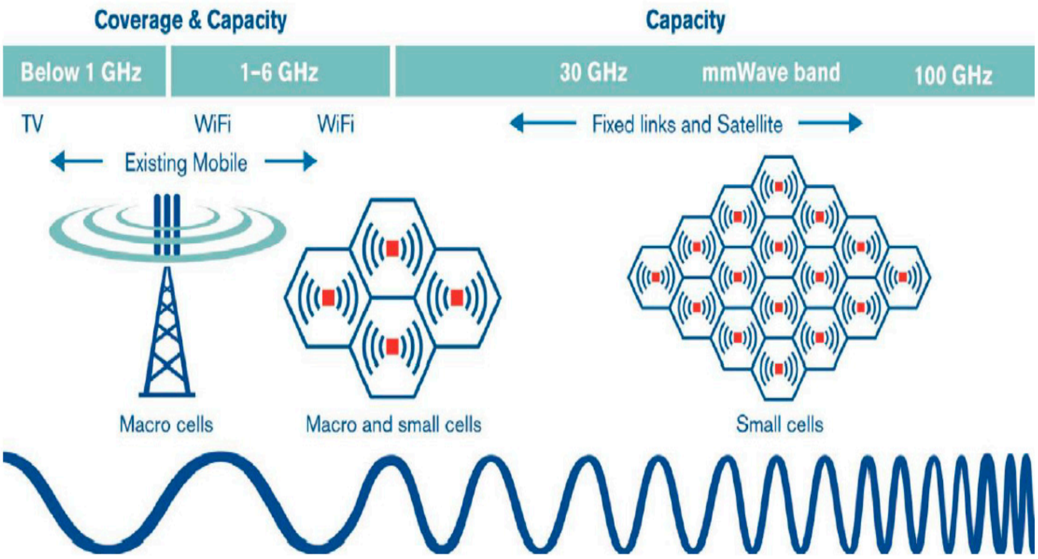


Figure 5. Spectrum ranges for 5G [32].

2.4. 5G Usage Scenarios

The goal of Industry 4.0 is to increase efficiency by incorporating the features of cutting-edge technologies into all processes and assets, as well as to provide a better understanding of manufacturing processes across their manufacturing sites in near real-time. The deployment of 5G has raised expectations that it will open new opportunities for manufacturing business models, given the expected increase in data requirements ranging from mission-critical to massive machine connectivity. As shown in Table 3, 5G promises faster download speeds, lower latency, and increased capacity.

Table 3. Comparison of 3G/4G and 5G latency times and data speeds [19,21].

Network Type	Average Download Speeds	Peak Download Speeds	Theoretical Download Speeds	Milliseconds (ms)
3G	8 Mbps	~20 Mbps	42 Mbps	60 ms (Typical)
4G	32.5 Mbps	90+ Mbps	300 Mbps	50 ms (Typical)
5G	130 Mbps–240 Mbps	599 Mbps+	10–50 Gbps	1 ms (Theoretical)

By automating industrial technologies and utilizing other enabling technologies such as artificial intelligence (AI) and machine learning, the manufacturing industry expects to maximize the innovations of 5G wireless communications. Industry expects this to lead to more precise decision-making, such as the automation of physical tasks based on historical data and knowledge, or improved outcomes for a wide range of vertical marketplaces, including agriculture, supply chain logistics, healthcare, and energy management, among others [30]. The use of network slicing is listed as follows: (a) eMBB (enhanced mobile broadband), (b) URLLC (ultra-reliable low latency communications) and (c) mMTC (mobile multimedia transmission control) (massive machine-type communications). By 2030, it is estimated that 5G technology will increase the global manufacturing gross domestic product by 4%, which is equivalent to approximately $740 billion [12,30].

The evolution of mobile communications has significantly affected socio-technical evolution in recent decades, by contributing to the economic and social development of both developed and developing countries. Mobile communications have become deeply ingrained in all aspects of daily life. The evolution of mobile communications systems and socio-technical trends are expected to remain tightly coupled, forming a foundation for the next generation of society in 2020 and beyond. Therefore, new demands, such as increased traffic volume, a greater number of devices with varying service requirements, improved quality of user experience (QoE), and improved affordability through cost reduction, will necessitate a greater number of innovative solutions soon. The potential user and application and technological trends, spectrum applications can be summarized to the following: (1) support very low latency and high reliability human-centric communication, (2) support very low latency and high reliability machine-centric communication, (3) support high user density, (4) maintain high quality at high mobility, (5) enhanced multimedia services, (6) Internet of Things (IoT), (7) convergence of applications, and (8) ultra-accurate positioning applications. Finally, Figure 6 presents the three major application scenarios for 5G [13].

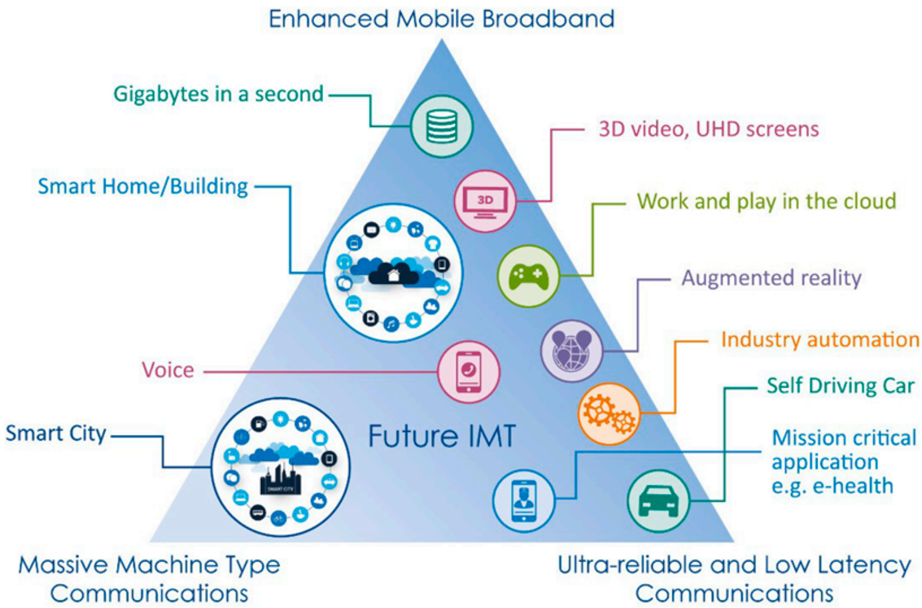


Figure 6. Three major application scenarios for 5G in 2015 defined by ITU [13].

The International Telecommunication Union Radiocommunication Bureau (ITUR) defines three typical application scenarios of 5G as illustrated in Figure 7.

- Enhanced mobile broadband (eMBB) is mainly for high-bandwidth demand services such as virtual reality (VR), augmented reality (AR), and online 4K video
- Massive machine-type communications (mMTC) is mainly for services with high connection density requirements such as smart cities and intelligent transportation
- Ultra-reliable low latency communication (uRLLC) is mainly for delay-sensitive services such as internet-of-vehicles, unmanned driving, and UAV (unmanned aerial vehicle)

2.5. The Potential of 5G in Manufacturing

The deployment of 5G wireless technology comes at a time when many industries are undergoing transformations due to increased automation, thanks to technologies like the IoT, machine vision, machine learning, and robotics. 5G connections are expected to enable the intelligent IoT, in addition to human communication needs. The next generation of telecommunication technologies (NextGen) will be adopted by a broader range of industries and sectors, with digital manufacturing being benefited. Next-generation wireless control of highly sophisticated mobile machines is becoming possible, allowing machines to take advantage of the massive computing power and cloud storage options, without being tethered by physical wires. To this end, factory [34] and machine shop [35] monitoring, in which sensors are installed in the shop-floor level to monitor equipment conditions and ensure that everything is working as it should. Additionally, with 5G technology real-time production monitoring will be possible, knowing the near real-time state of equipment or the expected manufacturing time after an order has been placed, with proper access from anywhere around the globe. As such, the various factors that have to be considered to define the business model and the pricing of a 5G industrial network are discussed in [36]. Next, in terms of predictive maintenance, the identification of potential issues before they occur, is an early area of interest for 5G in the IIoT [37]. Moving information and network functions to the network's edge can help reduce latency, which will be necessary for applications that require ultra-low latency. When dealing with lengthy distances between nodes, applications that must span end-to-end, such as remote machinery control, will require 5G at the very least. 5G latency can be divided into three network topologies, assuming a roundtrip ping scenario, as presented in Figure 8.

- Public cloud to device: 50 ms to 100 ms
- Telco cloud to device: 20 ms to 50 ms
- Telco edge to device: 1 ms to 2 ms

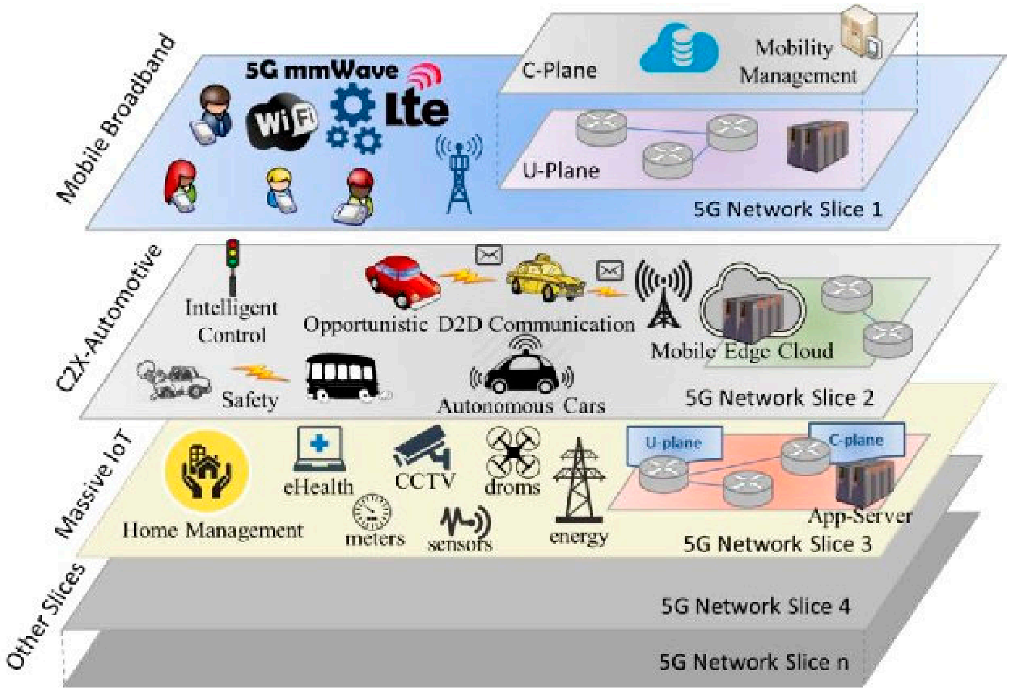


Figure 7. 5G network slices [33].

2.6. The Impact of 5G on Manufacturing

Close coordination across all systems, particularly information and communication technologies (ICT) and manufacturing operational technologies (OT), is necessary to leverage the inherent possibilities of 5G inside a production system. Industry will be able to create cyber-physical systems (CPS) that allow for near-real-time precision control from nearly any location on the planet. Some application examples of typical deployment scenarios are listed below [39,40]:

- Ability for remote control
- Remote control of supply chain equipment
- Remote equipment monitoring

- Support for augmented reality (AR) in design, maintenance (real-time), and repair: simulations are used in the design, maintenance, and repair domains to aid in the execution of procedural tasks
- Intra- and inter-enterprise communication

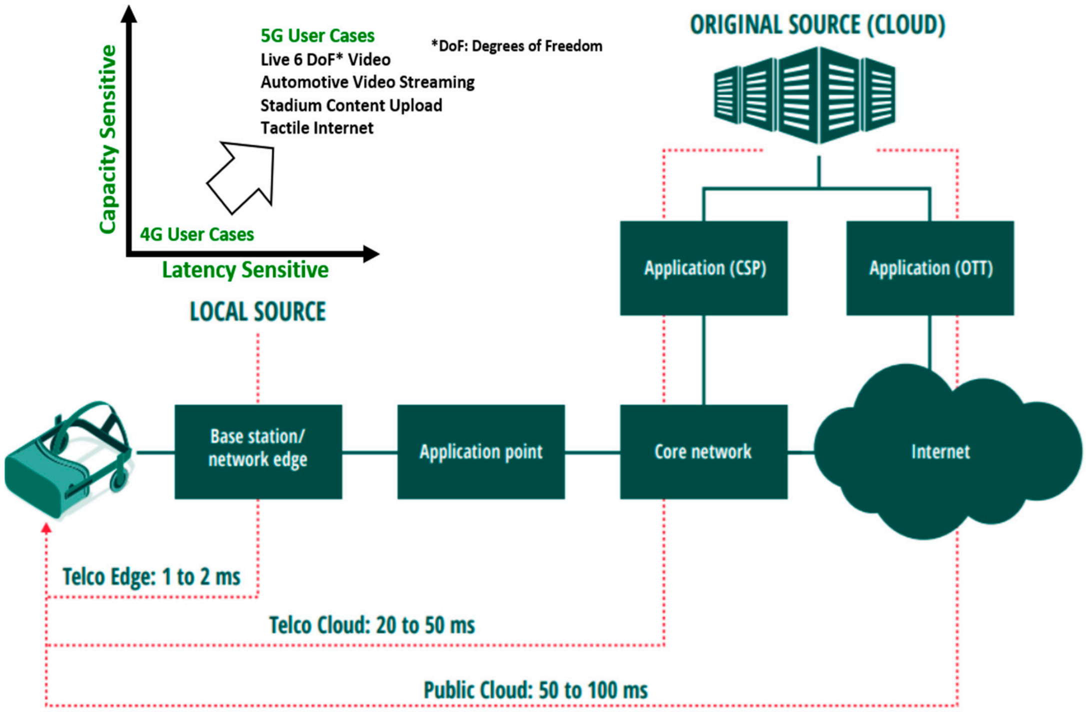


Figure 8. Different network topologies and their associated latencies [38].

2.7. Challenges for 5G and TI Adoption

Although mobile operators began to roll out 5G in 2019, this does not mean the technology will be ready for widespread use by manufacturers. Certain 5G features relevant to manufacturing use cases may not be available for at least another 5 years, and coverage in rural areas will be a challenge. The following are the primary identified hurdles for industry adoption of 5G based on the foregoing: (a) the cost of procuring and installing the required equipment, (b) safety, (c) deployment knowledge, and (d) RF interference. Finally, the expanding usage of more complex collaborative robots in production is a topic to consider (cobots). Cobots are already on the market, but the incorporation of 5G networks is expected to make them even more valuable. For example, taking use of 5G networks' decreased latency allows for more instantaneous real-time proximity awareness, allowing the robot to work at quicker speeds, adjacent to a human, while reducing the danger of injury [40].

2.8. The Latency Budget of a Data Life Cycle in the Tactile Internet

TI relies on the best response time, accessibility, dependability, and security. These objectives can be achieved by using distributed service platform architectures. Tactile applications must be implemented in locally available systems close to the clients due to the requirement for extremely low end-to-end latency [41]. Figure 9 depicts the various latency components of a typical TI system.

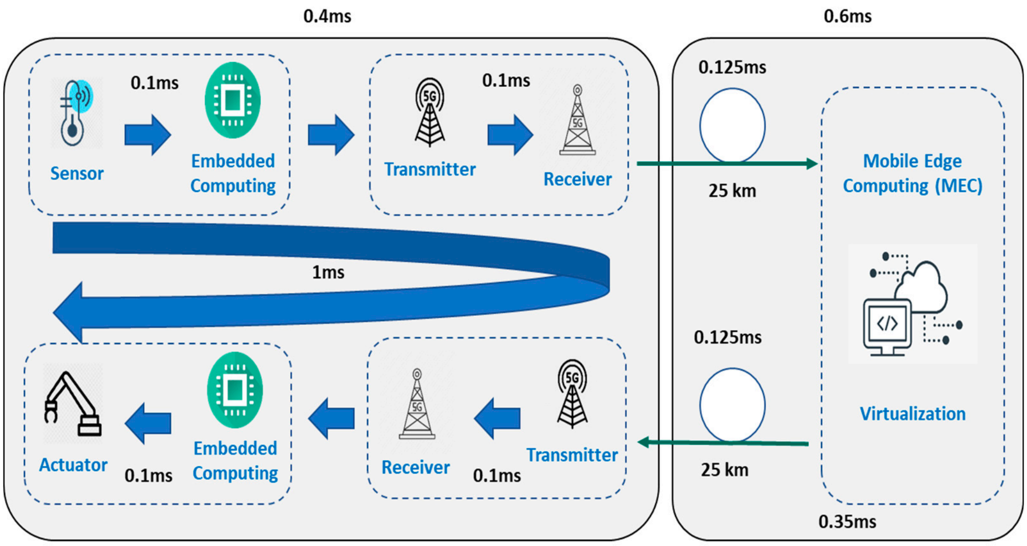


Figure 9. The various latency components of a typical TI system [41].

2.9. The Era beyond 5G

As discussed briefly in the Section 1, the next generation of mobile networks, known as "6G" or "Next G" is under development. More specifically, the first activities in North America are focused on research conducted by academic bodies in conjunction with standards developing organizations (SDOs). Europe has also granted research funds under the Horizon plan. However, it is notable that eastern countries, such as China and Japan have set up research teams for the research and development of 6G networking infrastructures and have funded multi-billion R&D projects. Therefore, the research community has already published the first wave of research works in the field. In the research work of Viswanathan et al. in 2020 [42], which has been supported by Nokia, the authors examine the key characteristics of 6G based on the recent technological advances. It is worth mentioning that 6G, besides the hardware infrastructure, will be heavily based on the artificial intelligence air interface management and optimization as well as on more dense networking as a result of the IoT. In [43] Jian et al. have conducted a comprehensive survey on 6G. One of the key outcomes of this survey is that 6G will enable new dimensions on mobile networking, and more specifically in the fields of extended reality (XR), TI, digital twin, pervasive intelligence, intelligent transportation/logistics, enhanced communications, multi-sense experience, and global ubiquitous connectivity. Similarly, in [44], the authors have also performed a survey on 6G. However, in this publication the authors mostly focus on the deployment challenges. Concretely, for the deployment of 6G, it is necessary to transition to the frequency band of THz (Terahertz), design more dense antenna networks, as well as define the communication protocols. Modulation techniques are also a cornerstone, in order to link 6G to the previous 5G and 4G. Among the most common and effective modulation techniques lie discrete Fourier transform (DFT) precoded OFDM and the OFDM which is already applied for the link between 4G and 5G (for a definition of OFDM please refer to Figure 1).

A key aspect in the development and deployment of 6G is the redesign of the so-called air interface. Briefly, air interface can be realized as the communication link between two devices, e.g., the mobile device and the antenna. Currently, in 5G, the applied interface is open radio access network, abbreviated as RAN. In [45], the focus is concentrated on the deployment of 6G in subnetworks where reliability and availability of the network is critical. Thus, by default, the connection is achieved through wired connection. However, 6G is a suitable candidate for wireless connectivity. On the other hand, it becomes evident that the key challenges in such deployments are interferences, including jamming attacks as well as impulsive noise.

Based on the lessons learnt from the deployment of 5G networks, specifically in the field of software support and network security, the authors in [46] have conducted research which emphasizes the environmental impact of 6G in terms of energy consumption. Under the spectrum of energy efficiency, one of the key goals for the deployment of 6G is to become approximately 100 (one hundred) times more efficient in comparison to 4G networks. The recent advances in 5G networks have indicated that software support is fundamental for the achievement of the goals set for this mobile network generation. Notably, the utilization of energy intensive servers, in contrast to the chips used in virtualized radio access networks (also known as RAN), has enabled 5G networks to deliver higher bandwidth at the cost of increased energy consumption.

Despite the key challenges and issues identified for the successful deployment of 6G networks in the previous paragraphs of this section, the capabilities offered are greater than any previous mobile network generation. Focusing on TI, which is the main theme of this research work, it has been enabled by the deployment of 5G networks. However, with 6G improved E2E (exchange-to-exchange), latency can be achieved, rendering feasible a system reaction time of 1 millisecond or even less, which is a cornerstone requirement for reaching the human sense time. Moreover, high reliability, availability, security, and throughput all add up to achieving real-time monitoring and system tele-operation. As a result of the increased bandwidth support, greater network traffic can be supported. For example in applications where sensor data as well as control data must be transmitted/exchanged, the distributed control systems (enabled by 6G), can manage network traffic more efficiently.

3. Application Fields of Smart Manufacturing and Tactile Internet Powered by 5G

Since the already defined challenges are met, 5G-based TI mobile communications can be used to explore and achieve a wide range of applications. As a result, Table 4 presents a taxonomy of possible TI applications with 5G frameworks and their requirements [17].

Table 4. TI applications based on 5G [17].

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

3.1. Industry

Modern manufacturing relies on the collaboration of multiple technologies, resulting in the generation of large data sets. With the ultra-low latency and high bandwidth capacity offered by 5G technology, this massive increase in data collection can be transmitted and analyzed much faster. The addition of multiple sensors to industrial facilities machine monitoring is generating more data than before. While the production floor is the most obvious location where 5G can benefit manufacturing, there are other ways in which 5G can contribute to the manufacturing environment in a non-direct way, as presented in Table 5 [47,48].

Table 5. Manufacturing use cases enabled by 5G [48].

Application	Use Case	Benefits	Why 5G?
Advanced Predictive Maintenance	Using dozens of sensors to give an accurate, real-time representation of the status of a machine to perform predictive and preventative maintenance	Reduce downtime Reduce speed on maintenance Reduce machine replacement rate	Reliability Device costs Device density
Precision Monitoring & Control	Real-time monitoring and control of robots/machine tools/end-product (e.g., change speed of process based on vibrations)	Reduce defects Increase throughput	Ultra-low latency Device density
Augmented Reality & Remote Expert	Using augmented reality headsets to guide worker via augmented display and/or remote expert when carrying out maintenance and repair tasks	Reduce spending (and time) on maintenance and repair Reduce spending on training	Ultra-low latency Bandwidth
Remote Robot Control	Controlling robotic machinery remotely (video link may be required) for tasks where human involvement may be hazardous	Health and safety Increase throughput	Ultra-low latency
Manufacturing-as-a Service	Making manufacturing flexible and mobile by reducing time to set up a site (fixed infrastructure) and enabling multiple parties to use same facility	Increase rate of product innovation Reduce overall costs Increase productivity	Flexibility Device costs Ubiquity
Automated Guided Vehicle	Coordinating vehicle control of AGVs (e.g., forklifts, pallet movers or tractors) in a more flexible way without needing to pre-define routes	Increase efficiency and productivity	Low latency Reliability Location-awareness
Drone Inspections	Using drones to perform tasks that may be difficult, dangerous, or tedious for humans (e.g., inspecting hard to reach equipment, checking inventory)	Health and safety Reducing spending (and time) on inspections	Low latency Reliability Location-awareness

Industry digitalization is already happening, opening up new opportunities for service providers. With 5G, industries all over the world can innovate and rise to their full potential. Ericsson and Audi have been working together to use 5G technologies to broaden the horizons of tomorrow's factories. They first introduced a safe AGV operation over a 5G network, and now 5G URLLC has taken factory automation over a wireless network to the next level. Similarly, Ericsson and Audi have built a robot cell similar to those used in Audi factories today, but over 5G connectivity, in the latest demonstration showcasing the power of 5G ultra-reliable low latency communication (URLLC) [49]. To avoid system safety stops, 5G URLLC provides very low latency and strict latency bounds with required guarantee levels. This is of great significance for the industrial automation industry, as it opens the door for safe human-robot interaction and path planning for UAVs in indoor manufacturing environments [50]. Based on the abovementioned, 5G can improve existing Smart Manufacturing use cases, and enable future ones. In terms of the delivered capabilities, the use cases that are being realized today will continue to evolve and expand. This progression will necessitate not only a larger network footprint, but also higher network performance, which future 5G IoT deployments may well be able to provide. Furthermore, manufacturers are investigating several novel use cases that are currently unattainable with the technology in place, as presented in Figure 10 [51].

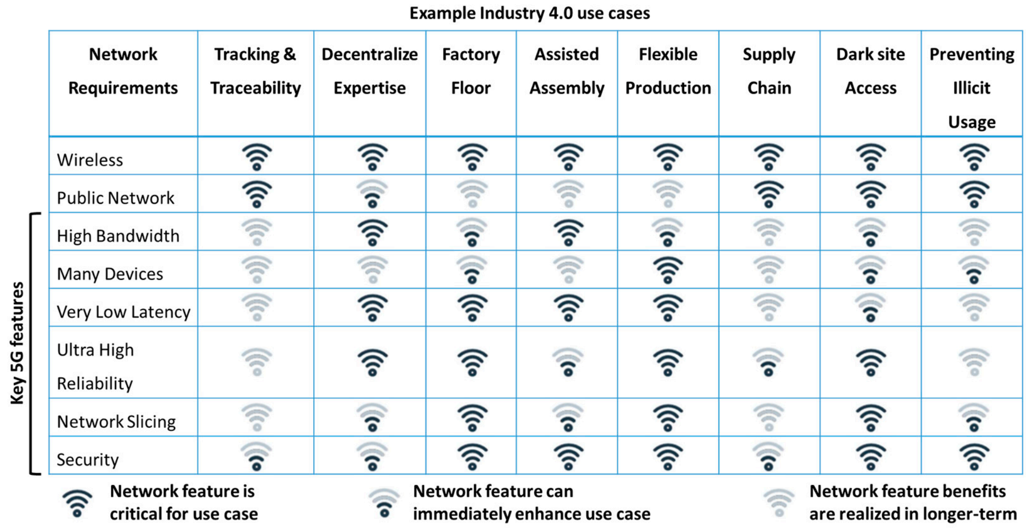


Figure 10. Existing and future use cases aligned to 5G technical capabilities [52].

3.2. *Virtual Reality and Augmented Reality*

A taxonomy for TI deployment in real-time ultra-reliable low latency (URLL) applications such as Healthcare 4.0, Industry 4.0, virtual reality and augmented reality (VR/AR), and smart education is illustrated in Figure 11. TI is used in all these applications to improve communication, minimize latency, increase bandwidth and reduce overall operational and capital expenditures [53].

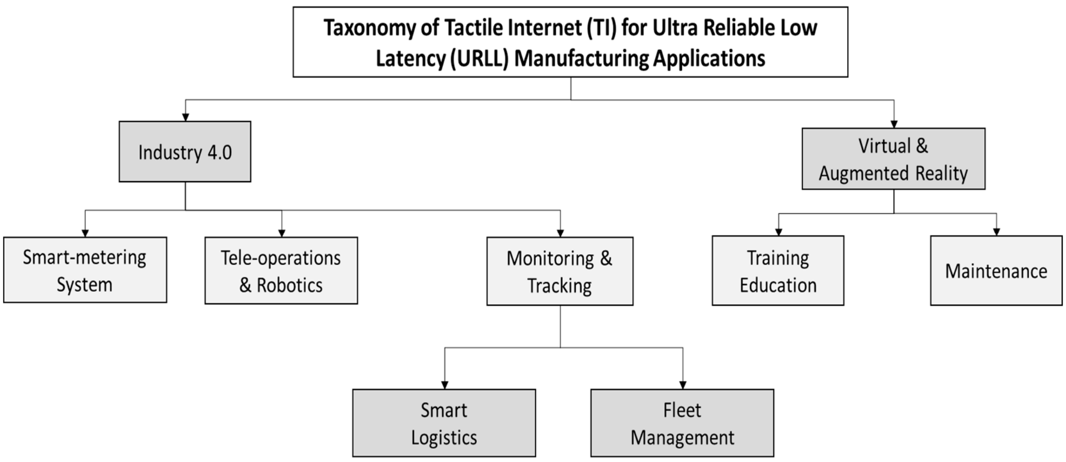


Figure 11. Taxonomy of TI for URLL MFG applications (adapted from [8]).

The tactile internet will benefit virtual reality (VR) by enabling 'shared haptic virtual environments', in which several users are physically coupled via a VR simulation to perform tasks that require fine motor skills, as presented in Figure 12. High-fidelity interaction requires haptic feedback, which allows the user to perceive objects in VR not only through audio-visual means but also through touch. This enables delicate object manipulations, such as those required in telesurgery, micro-assembly, or other applications requiring extreme sensitivity and precision. When two users interact with the same object, the VR creates a direct force coupling, and the users can feel each other's actions. However, communication delays in today's networked VR systems are too great for stable, seamless user coordination. High-fidelity interaction is only possible with a few milliseconds of communication latency between the users and the VR. During these few milliseconds, the users' movements must be transmitted to the VR server, which computes the physical simulation and returns the results to the users in the form of object status updates and haptic feedback. Therefore, even wired communication may be insufficient for remote users. Typical update rates for physical simulation and haptic information display are in the 1000 Hertz range, corresponding to an ideal round-trip communication latency of 1 millisecond. A consistent local view of the VR for all users is thus only possible if delays are kept to a minimum [53,54].

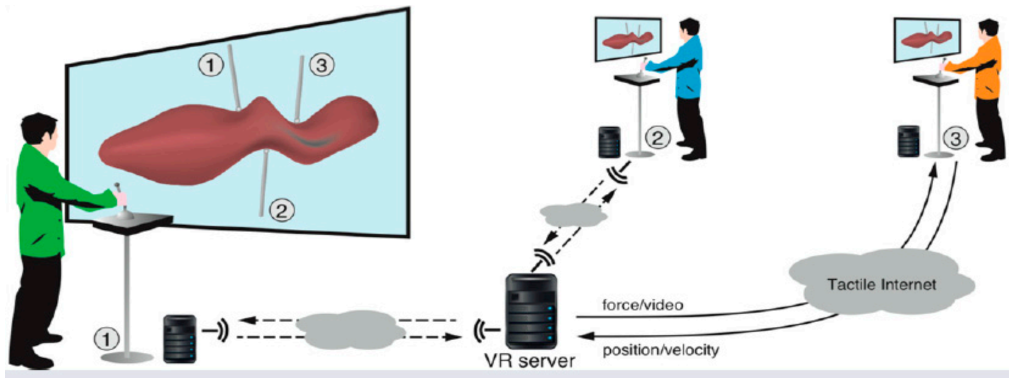


Figure 12. Physical coupling of several users via VR simulation with haptic feedback [13].

Additionally, the authors in [53] describe the statistical characteristics of control and haptic feedback signals, as well as virtual reality-based human-to-machine (H2M) experimental setup. Next, the volume of input and output data in any H2M experimental setup is determined by hardware design parameters such as sampling frequency, the number and type of sensors and actuators [55]. The slave haptic subsystem can be a physical device that interacts with a remote physical environment or a virtual pointer that operates in a virtual environment, such as a virtual hand. Simulated virtual worlds can connect multiple users in a virtual space over a local network. Therefore, a VR-based H2M experimental setup, was developed to investigate the characteristics of control signals from a master device and the corresponding haptic signals from a slave device. The master device consists of a pair of VR gloves, each with two 9-degrees-of-freedom orientation sensors on the thumb and wrist, as well as five flexible sensors on the five fingers for tracking movements and applied forces.

To summarize, in order to establish a truly immersive VR user experience, there is still a lot of work to be done. The VR quality of experience is greatly reliant on strict latency and reliability standards. Motion sickness is caused by high message transfer part (MPT) delays of 20 milliseconds or more, as well as distortions caused by low data rates and the consequent quality of projected images. As a result, an immersive VR experience requires end-to-end delay and reliability. Figure 13 depicts the expected requirements as well as the key technological enablers for single and multiple user VR scenarios. Then, as two primary thrusts of the future interconnected VR, the envisioned roles of mmWave communications and mobile edge computing (MEC) are also highlighted.

3.3. Education

During Industry 4.0, engineers have focused on the digitization and digitalization of manufacturing and production systems, i.e., the machine-to-machine (M2M) interface. As a result, modern equipment is already, or soon will be, a thing on the internet (Internet of Things (IoT)). Consequently, machines/systems have become smarter, and are capable of producing and utilizing data (see big data sets). On the other hand, in order to achieve a harmonic coexistence between humans and machines, it is imperative to focus on improving the human-to-machine interface (HMI), which is the central concept of the adaptive, cognitive, human-centered manufacturing initiatives around the world. Therefore, in order to overcome the emerging challenges, education is a key driver for the next generation of engineers. Further to this, new engineers require different skills that will enable them to communicate/coexist with machines more easily/intuitively. This is similar to the skill gap between the current generation and the previous generation which have been directly impacted by the introduction of computers in our everyday lives.

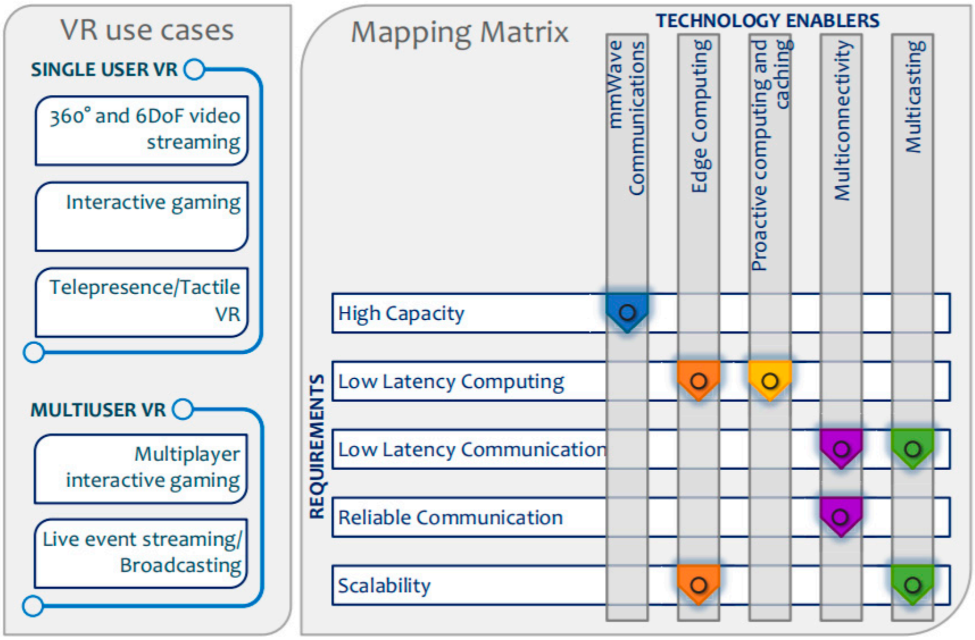


Figure 13. Single and multiple user VR use cases: requirements and enablers [56].

The 5G-based TI will enable enhanced learning based on the educator and learner's haptic overlay. Comprehension-based learning will increase learner interest and outperform traditional learning methods by combining TI with VR and AR. Following that, the learner will look for opportunities to adapt in general by exploring and discovering the available content. Additionally, there will be less interference from the educator and no educator pressure on the learner to study. The incorporation of VR-based study-related applications into the learner's curriculum would immerse the learner in tactile learning by allowing them to touch virtual objects that provide haptic feedback [57].

3.4. Healthcare

As regards healthcare, it is easier to comprehend the context by taking into account the Japanese initiative entitled "Society 5.0". In this initiative, it becomes apparent that the contribution of advanced HMI and the progress made so far during the last industrial revolutions (including Industry 4.0) extends beyond the limits of industry, up to the society we live in, and the companies operate in as well. Further to that, the ultimate goal of engineers is to discover new ways to address human issues. Taking into account the previous statement, healthcare is a crucial part of Industry 5.0. A distinctive example is the remote operations (also known as tele-operations), which require the cooperation of humans and robotic manipulators in real-time. Further to that, ultra-fast, highly reliable, and with near-zero latency network connections are required in order to achieve the seamless cooperation between humans and machines.

Tele-diagnosis, tele-surgery, and tele-rehabilitation are just a few examples of the tactile internet's potential applications in healthcare. Medicinal learning could be accessible from anywhere and at any time, regardless of the doctor's location, thanks to advanced tele-demonstrative tools. The doctor will control a tele-robot at the patient's location, which will provide audio and/or visual data as well as haptic feedback. Tele-surgery applications are linked to the same specialized guideline. Tele-rehabilitation methods can be used to help patients guide and control their movements from a distance. To enable the transmission of tele-medical innovation, high devotion and great precision are required in all tactile internet-based healthcare advances [58].

4. A Generalized Framework for Tactile Internet in the beyond 5G Era

Based on the abovementioned literature research, the generalized architecture of a TI system, consists primarily of a master domain, a network domain, and a controlled domain. Concretely, the master domain typically consists of a human operator (tactile user) and the human system interface (HSI), which oversees converting human input into tactile data using appropriate tactile encoding techniques. The HSI generates tactile data, which is sent to the controlled domain via the network domain. The controlled domain or environment contains a remotely controlled robot or tele-operator, and the master domain directly controls the controlled domain using various command signals (e.g., velocity, position). The controlled domain then sends feedback signals to the master domain (e.g., force/position, surface texture). The master domain receives audio/visual feedback signals from the controlled domain in addition to haptic feedback signals. As shown in the Figure 13, this communication domain could be made up of an internet/core network, a radio access network (RAN), and a tactile support engine. In addition, the underlying communication channel must meet several requirements, including ultra-responsive and ultra-reliable connectivity [59]. The main functions of a beyond 5G (B5G) core network to support a TI system are the handling edge-cloud interactions and access, application-aware quality of service (QoS) provisioning and security [60].

4.1. Master Section

The master section is located at the TI system's front end. It includes a human operator as well as a tactile human system interface (HSI). The human input is then converted into tactile input by HSI. HSI refers to a master machine or robot that serves as a haptic device. In the real world, a user is allowed to touch, feel, and manipulate. The operation of the slave is controlled by the master section via command signals. It should be noted that in most applications, multiple operators can work together to control the slave section's activities. The audio and visual feedback features are critical for haptic and non-haptic slave section control. As a result, it is critical to improve perceptual performance because the human brain typically coordinates diverse with tangible approaches [61].

4.2. Control/Slave Section

The slave section includes a tele-operator (slave robot) and is controlled by the master section via various coding techniques and haptic input command signals. In the remote environment, the tele-operator executes multiple actions as directed by the master section. Furthermore, the slave section has no prior knowledge of the surrounding environment. As such, a global control loop is formed when communication between the master and slave sections is initiated via feedback and command signals. A characteristic example of the 5G tactile internet slave section is the robotic tele-surgery [62].

4.3. Network Domain

This section is typically located between the master and control/slave domains and serves as a two-way communication medium, connecting the operator to the tele-operator (remote) environment. It is made up of routers and gateways, which provide a medium for two-way communication. The master domain sends the haptic input command signals. Thus, the input signals are routed through routers, switches, gateways, base stations, access points, a database server, and an AI-enabled tactile support engine before reaching the slave section [59,63].

5. Integrating 5G and Tactile Internet to Industrial Case Studies

Although the production floor is the most obvious location where 5G can benefit manufacturing, there are other ways in which 5G can contribute to the manufacturing environment in a non-direct way. The IIoT is used to integrate the equipment resources in the implementation of smart factories. As a result, the manufacturing system has perception, interconnection, and data integration capabilities. Further to that, the internet of services consists of interconnection, collaboration, and execution. Consequently, to transform a modern factory into a smart factory, key technologies in all layers must be thoroughly investigated [64]. Next, Figure 14 depicts the smart factory as being divided into several layers with different network choices at each layer; each network has different demands and values various properties differently. The level of integration that 5G can bring to manufacturing will be determined by decisions made at each of these levels. Network slicing, a key new concept in 5G, will allow tenants to get different levels of connectivity from their service provider to accommodate different use cases. 5G will be an all-cloud architecture to achieve network slicing, which will necessitate the use of software defined networking (SDN) and network function virtualization (NFV) (see Figure 15).

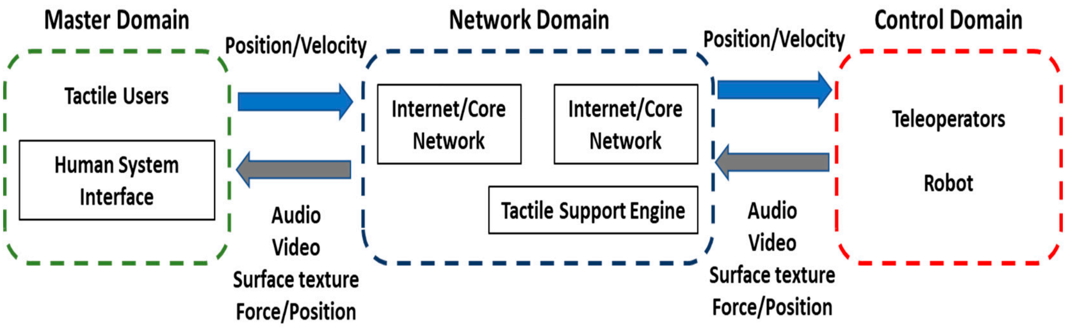


Figure 14. A generalized architecture of a wireless tactile internet system (adapted from [60]).

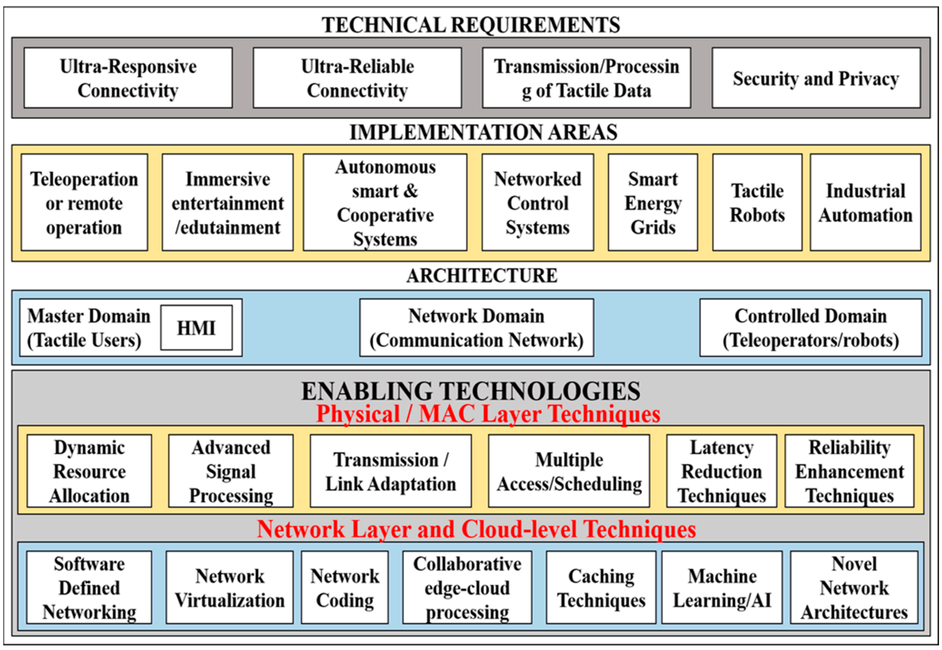


Figure 15. A generalized framework for TI in the beyond 5G era (adapted from [65]).

5.1. Integrated and Adaptive AR Maintenance and Shop-Floor Rescheduling Framework

Following the generalized architecture of a wireless TI system that has been presented in previous sections, the authors have used, as a reference framework, the published research work in [66] in order to integrate the necessary layers and ICT infrastructure towards 5G enabled tactile internet. The added layers and ICT components have been highlighted with the color green, as presented in the conceptual framework of Figure 16. Based on this architecture the following points can be stressed:

- There are different network choices at each layer of the smart factory
- The key new concept of network slicing in 5G will enable tenants to gain different levels of connectivity from their service provider to accommodate various use cases
- To achieve this network slicing, 5G will be an all-cloud architecture and this will ultimately require the use of software defined networking (SDN) and network function virtualization (NFV)

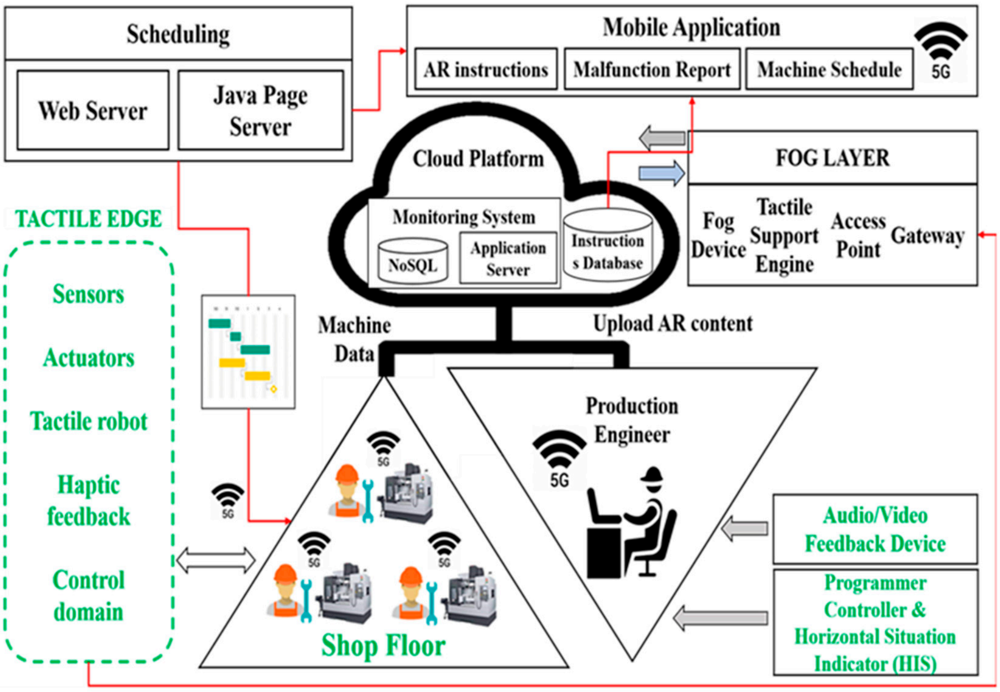


Figure 16. Integrating 5G and TI applications for integrated and adaptive AR maintenance and shop-floor rescheduling (adapted from [67]).

5.2. Real-Time Remote Maintenance Support Based on Augmented Reality (AR)

Cutting-edge digital technologies in the field of extended reality (XR), such as augmented reality, have entered the mainstream (AR). Furthermore, cloud computing, and recently 5G technology, have made it possible to provide high-quality services, particularly in the field of maintenance. However, as modern machines become more complex, maintenance must be performed by experienced and well-trained personnel, while overseas support is both timely and costly. Although augmented reality (AR) is a backbone technology that enables the development of robust maintenance support tools, it is limited to the provision of predefined scenarios that cover a limited number of scenarios. This research work aims to address this emerging challenge by designing and developing a framework for the support of remote maintenance and repair operations based on AR, by establishing appropriate communication channels between shop-floor technicians and expert engineers who use real-time feedback from the operator's field of view. The applicability of the developed framework has been tested in a lab-based machine shop and in a real-life industrial scenario. As illustrated in Figure 17 we have elaborated the proposed framework and the added layers and infrastructure towards 5G enabled tactile internet are highlighted in green.

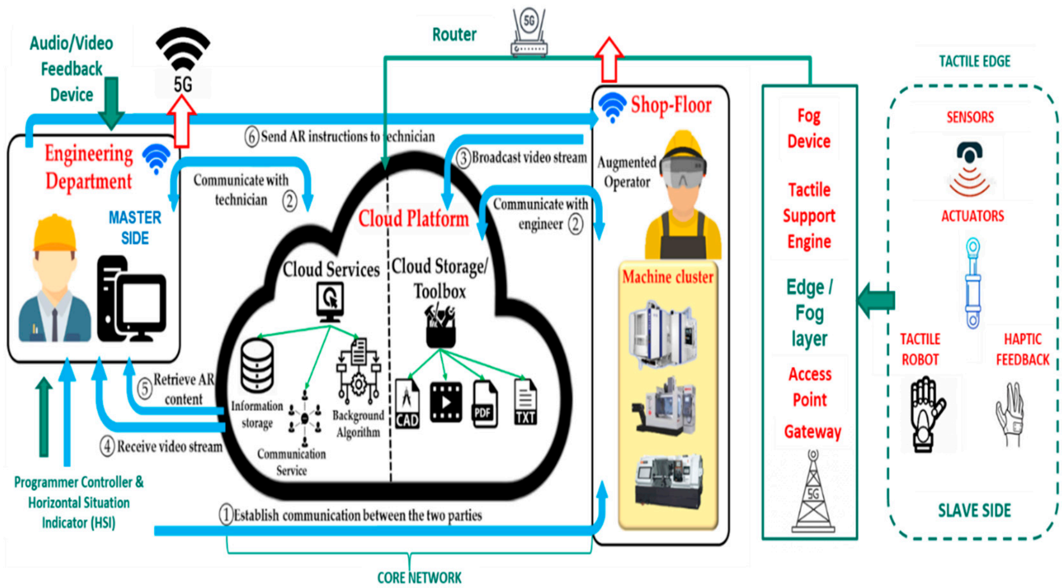


Figure 17. Integrating 5G and TI applications for integrated and adaptive AR maintenance and shop-floor rescheduling (adapted from [59]).

5.3. Integrating 5G and Tactile Internet to Educational Teaching Factory Case Studies

Over the last few years, communication latency has been a significant barrier for many applications deployed in various network domains. Until now, the Internet of Things (IoT) allowed the interconnection of low-power, limited-transition sensors, and latency-tolerant smart devices. Despite the advancement of communication protocols and standards, the latency problem persists, lowering the quality of services (QoS) and quality of experience (QoE) in many applications. As a result, the tactile internet's high availability, security, and ultra-fast reaction times will add a new dimension to human-machine interaction by enabling haptic and tactile sensations. Furthermore, the tactile internet can thus be used as a backbone for delay mitigation in collaboration with 5G networks, particularly for ultra-reliable low latency applications such as smart healthcare, virtual and augmented reality, and smart education and e-Learning. To address these challenges, the authors in [67] identified the challenges and opportunities highlighted by the integration of the tactile internet and emerging 5G systems in modern education. A framework for the fusion of a virtual, simulated machine shop to its physical counterpart is presented in Figure 18 within the scope of a teaching factory [68], highlighting the key aspects for successful human-machine interface (HMI) and real-time communication of the physical and digital machine shop.

5.4. Architecture of Smart Manufacturing Oriented 5G-Based IIoT

This section describes a 5G-based IIoT architecture based on the various Smart Manufacturing scenarios and the three communication modes of 5G wireless communication networks. The implementation methods of seven related Smart Manufacturing application scenarios are investigated in the context of 5G wireless communication technology, including real-time data collection of heterogeneous factors on the manufacturing shop-floor, identification and location of production factors, networked collaborative manufacturing, man-machine interaction, automated guided vehicles (AGV) collaboration, digital twin driven shop-floor convergence between physical and cyber space, product design, manufacturing and maintenance based on virtual and augmented reality. Big data, cloud computing, edge computing, digital twin, virtual reality/augmented reality, and service-oriented manufacturing are all discussed in detail as ways to apply advanced technologies based on 5G wireless communication technology in the architecture of 5G-based industrial Internet of Things (IIoT) [69].

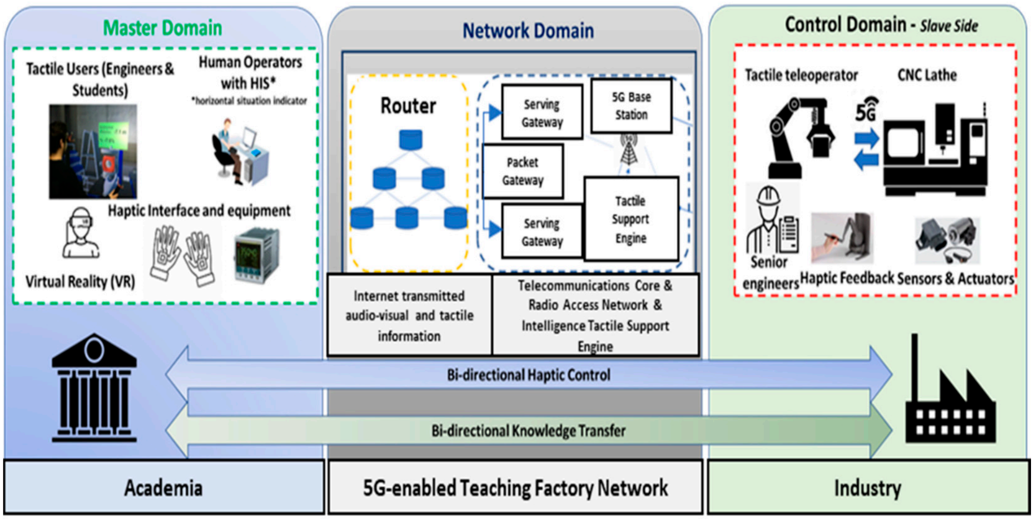


Figure 18. A generalized architecture of a wireless tactile internet system in a teaching factory [69].

The IIoT is used in the implementation of smart factories to integrate the underlying equipment resources. As a result, the manufacturing system has perception, interconnection, and data integration capabilities. In a smart factory, data analysis and scientific decision-making are used to achieve production scheduling, equipment service, and product quality control. In addition, the internet of services is used to virtualize manufacturing resources by moving them from a local database to a cloud server. The global collaborative process of intelligent manufacturing oriented to the order-driven market is built through human-machine interaction. As a result, the smart factory is an engineering system with three main components: interconnection, collaboration, and execution. The architecture of a smart factory [67,70] includes four layers, including a physical resource layer, a network layer, a data application layer, and a terminal layer. In order to transform a modern factory into a smart factory, key technologies in all layers must be thoroughly investigated, as shown in Figure 19.

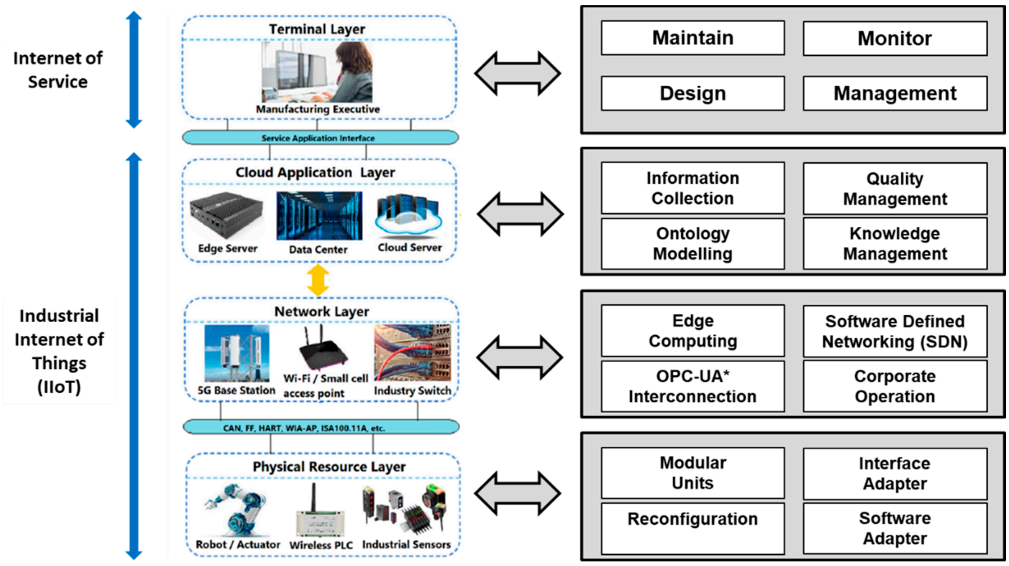


Figure 19. Hierarchical architecture of a smart factory (adapted from [71]).

5.5. New Developments in Wi-Fi for IIoT

The modern factory is a complex environment. Advanced machines and robots are equipped with a wide of sensors that connect to cloud-based analytics engines that evaluate performance, manage production schedules, maintain supplies, and orchestrate all factory activities. 5G will give the high-speed manufacturing environment far more flexibility by eliminating the need for wired connectivity. The 5G's technology specifications far surpass those of other wireless protocols, summarized in Table 6.

Table 6. Real-time high-capacity, low latency 5G applications (adapted from [72]).

Feature	Description	Wi-Fi6	4G	5G
Latency	Delay between the sender and receiver of the data—the lower the latency, the more 'real-time' the experience of the event	20 milliseconds (ms)	30–50 ms	1–10 ms
Reliability/ Availability	How efficient the network is in transporting data between the source and destination without packet loss	99.99%	99.99%	99.99%
Throughput	Theoretical maximum amount of data moved from one place to another in a given period	9.6 Gbps	300 Mbps–1 Gbps	10 Gbps
Speed	Expected practical speeds per user or device	1 Gbps	20–50 Mbps	Up to 1 Gbps
Connection Density	Number of connected devices per unit area	8 per part	12 per part	100 per part
Energy	Comparative power consumption levels	Medium	High	Medium

6. Security Considerations within 5G

5G meets IoT requirements that have never been met before in terms of bitrate, latency, reliability, and many other factors. However, because the general lack of security in IoT systems has not been addressed, this section discusses how security considerations in 5G, in relation to IoT scenarios, have been addressed in the literature. By the time 5G is a wireless communication network, many of its security schemes and solutions will be derived from other wireless technologies. However, because it uses licensed spectrum, the main security concerns are inherited from legacy cellular networks, such as long-term evolution (LTE). As a result, 5G is developed with a flexible security scheme and methods to deal with new requirements arising from a large number of potential use cases where 5G will be used. Moreover, it supports new trust models as well as new threat-handling models, and finally, to handle MMTC (massive machine type communications) traffic and management and a large number of different types of connected devices. As already discussed, the control and user planes are separated in layers and therefore network mechanisms are implemented in a different way than the cellular networks. 5G provides several advantages for IoT and IIoT systems, including low latency, high speed, and many others, but it also introduces the abovementioned concerns. 5G-enabled IoT is a state-of-the-art topic and lots of proposed solutions are emerging, allowing 5G to be an optimal communication platform for IoT. The greatest advantage of 5G in terms of IoT security is the flexibility of the system, which allows for efficient, use-case-specific solutions. An effective way to improve security is by using PLS solutions and lightweight cryptography techniques so as to improve security on low-powered nodes, which are major drivers of IoT. The main security concerns are identified as follows: (1) common attacks in communication networks, (2) attacks towards control plane, (3) cloud-based SDN and VFN issues, (4) traditional IoT issues, and (5) attacks towards low-powered nodes [73]. Consequently, the abovementioned issues raise new security threats and challenges, as presented in Table 7.

Table 7. Security challenges in 5G technologies (adopted from [74]).

Security Threat Description	Targeted Network Element	Technologies Prone to Attacks				Is Privacy Compromized?
		Software-Defined Networking (SDN)	Network Functions Virtualization (NFV)	Channels	Cloud	
Configuration attacks	SDN (virtual) switches, routers	✓	✓			
Denial of service (DoS) attack	Centralized control elements	✓	✓		✓	
Hijacking attacks	SDN controller, hypervisor	✓	✓			
International mobile subscriber identity (IMSI) catching attacks	Subscriber identity			✓		✓
Penetration attacks	Virtual resources, clouds		✓			
Saturation attacks	SDN controller and switches	✓				
Signaling storms	5G core network elements			✓	✓	
Man-in-the-middle attack	SDN controller-switch communication	✓		✓		
Transmission control protocol (TCP) level attack		✓		✓		
Reset and IP spoofing	Control channels			✓		✓
Scanning attacks	Open air interfaces			✓		✓
Security keys exposure	Unencrypted channels			✓		✓
Boundary attacks	Subscriber location			✓		✓
Semantic information attacks					✓	✓
Timing attacks						✓
User identity theft	User information data bases				✓	✓

Based on the abovementioned, critical security capabilities will be required at the device and network levels to address complex applications such as smart cities, smart networks, and so on. Security is extremely complicated in the diverse 5G-IoT systems. The designer must consider not only remote software intrusion, but also local intrusion at the device level focusing on avoiding the following security links [75]:

- Identity
- Authentication
- Assurance
- Key management
- Crypto algorithm
- Mobility
- Storage
- Backward compatibility
- Assurance

7. What beyond 5G Should Look Like

The exchange of data between physical space and cyberspace is expected to significantly increase during this decade (2020–2030). Physical interactions in physical space will be replicated in the form of digital data in cyberspace as the integration of cyberspace and physical space (cyber-physical systems (CPS)) progresses. Using AI to analyze such vast amounts of digital data will allow us to not only grasp the current state of physical space, but also to make decisions about future actions in physical space based on that information. CPS is expected to grow in line with the introduction of 5G, which offers a number of benefits including low latency and a large number of simultaneous connections in addition to high speeds. As a result, cyberspace will not only expand the functions of physical space, but it will also create a society that is both robust and resilient, with daily lives and economic activities fully maintained within cyberspace, even if there are unexpected crises in the physical world. This is expected to enable not only further progress in resolving social challenges and generating economic growth in Japan, but also to significantly contribute to the realization of the principles outlined in the Sustainable Development Goals (SDGs) [76]. The three elements listed below can be viewed as specific goals for a vibrant and resilient society (Society 5.0) in the 2030s.

- The first is an inclusive society in which everyone can participate actively by eliminating differences such as age and disability, as well as geographical barriers such as urban and rural areas and national borders. The realization of such a society will necessitate, for example, super tele-presence technologies that will allow people to feel as if they are physically present anywhere in the world via an avatar, robot, or other means without having to leave their own home.
- The second is a sustainable society in which society can achieve sustainable growth while remaining convenient, with no social loss, by optimizing cyberspace with real-world reproduction that can be fed back into the real world.
- The third is a dependable society, a human-centered society in which trust bonds are unbreakable and everyone can work in peace by autonomously ensuring the safety and stability of communications networks as a social infrastructure.

The progress of CPS towards a Society 5.0 era with a 5G-centered information and communication technologies (ICT) infrastructure is presented in Figure 20.

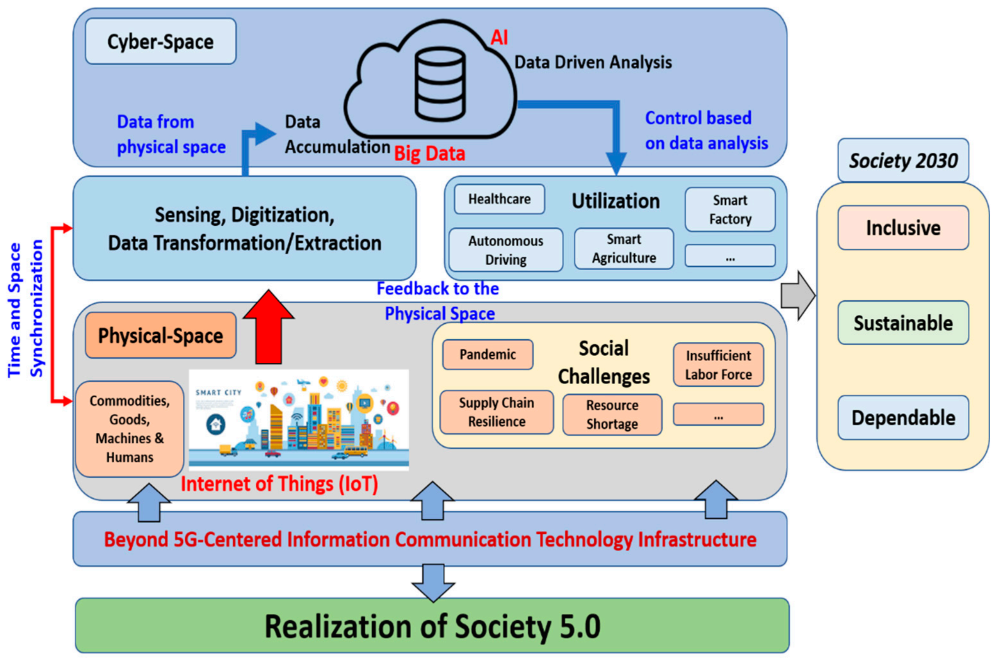


Figure 20. Progress of cyber physical system and society in the 2030s (adapted from [77]).

8. Conclusions

In the future, wireless networks beyond 5G are expected to support a wide range of new TI applications with varying QoS requirements. Due to the need to communicate haptic information in addition to the traditional audio and visual traffics over wireless media, several non-conventional challenges have arisen and have to be addressed. Ultra-low latency, ultra-high reliability, very high data rate, energy efficiency, spectral efficiency, and network throughput are the main technical requirements in this regard. To this end, this paper has presented a comprehensive survey on various aspects of wireless TI, beginning with TI's vision and recent advances as well as a generalized framework for wireless TI, which includes the main technical requirements, key application areas, a TI architecture, and the main enabling technologies. Furthermore, key enablers for supporting TI applications/users in B5G systems, as well as the main sub techniques, have been identified and discussed. Finally, as it impacts the steps that are required by the manufacturers side, it is necessary to learn about 5G, its benefits and drawbacks, as well as how it will interact with other technologies that are already used. Next, the manufacturing industry should contribute to the development of 5G standards and regulations so that the technology meets their needs, and last but not least to collaborate with telecoms operators to shape how they commercialize 5G in the market and ensure that they are an integral part of this developing ecosystem.

Moving on, as it regards future work, future 5G networks will need to have significantly more system capacity than current networks in order to avoid a spectrum shortage. In order to successfully integrate a 5G network in modern manufacturing environments, many infrastructure improvements will be required. The requirements will range from upgrading the backbone infrastructure of the organization to developing a suitable strategy for managing the use of the following: (1) spectrum adoption, (2) fiber rollout internally (10 Gb minimally), (3) high-speed switches and routers, (4) on-site, and (5) deploying edge-connecting devices. Future research will focus on the wireless AR/VR investigation and the suitable B5G network architecture that can deliver AR/VR capability and to identify interfaces to connect AR/VR devices with wireless network. Additionally, one more issue to be investigated is the advanced signal processing techniques in order to use low-complexity machine learning techniques to extract the meaningful information from raw data acquired by tactile sensors computing.

Author Contributions: All authors have participated in the modelling of the research project. More specifically: supervisor, D.M.; research, conceptualization, and original draft preparation, J.A.; research, conceptualization, and original draft preparation, N.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

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