The 1-Millisecond Challenge – Tactile Internet: From Concept to Standardization

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Abstract: In recent years, Tactile Internet (TI) has become a familiar concept to humankind. It is expected to have the potential to create many new opportunities and applications that reshape our life and economy. However, the biggest challenge for recognizing the TI – the "1-millisecond challenge" remains unchanged, and it requires additional research efforts. In this paper, we will dissect what has been done and what needs to be done for the "TI ecosystem". We will also investigate the TI concept from the perspective of the "network latency evolution", as well as analyzing the architecture and the emerging technologies, which are needed to meet the strict requirements of the TI.

Keywords: Tactile Internet, Internet of Skills, Haptic Communication, 1-millisecond challenge, latency.

1. Introduction

Today's world has witnessed the emergence of various Internet generations. As we all know, the first generation is the fixed Internet, which created extensive connections between computers, allowing users to interact with each other regardless of geographical location. The second generation is the mobile Internet, adding flexibility and convenience to users by combining telecommunication infrastructure with the Internet (Salkintzis, 2004). Therefore, people could connect virtually anywhere, any time. As a result, the number of Internet users, as well as mobile devices, increases quickly. With the increasing number of users, it would open a new direction for the next generation of the Internet, where everything and every object can be connected to the Internet to create the Internet of Things (IoT) (Gubbi *et al.*, 2013). An

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important question to be addressed is: "What will the future Internet be after the era of IoT?" (Cao, 2017). Scientists have now begun to discuss an entirely new Internet generation – Tactile Internet (TI) (Fettweis, 2014; Dohler, 2015) or Internet with ultra-low latency for the evolution of the IoT.

In this paper, we aim to investigate the concept of the TI from a perspective of technologies and applications while highlighting some challenges in this respect. Although some researchers provided general descriptions of the TI, they only focused on some aspects of the TI. This paper reviews all the aspects of the TI: concept, requirements, architecture, technologies towards the TI, the relation with new concepts (such as Internet of Skills (IoS) and Haptic Communication (HC)), applications, and standardization. The main contributions of this paper are as follows:

- The paper investigates the TI based on the evolution of the latency in the network: NGN network – Medical network – TI network;
- The paper summarizes all different definitions of TI concept;
- All emerging technologies towards TI from the point of "1-millisecond challenge" are described.

The standardization process and contributions from various companies and alliance groups are summarized at the end of the paper to help readers get a general overview of the TI ecosystem.

1.1. The evolution of latency in network and telecommunication systems

The cornerstone of the TI concept is the evolution of latency in network and telecommunication systems under the increasingly stringent requirements of new applications and services. The latency problem has been noticed since the stage of the packet switching network Next Generation Network (NGN) (Hany, Hossain & Saha, 2010). The latency should not exceed 100 ms (ITU-T Y.1541, 2015) to ensure the quality of audio and video communications for the users in the same quality as in the Public Switched Telephone Network (PSTN). This problem has been resolved. However, in recent years, some new applications and services have emerged, especially in the medical industry. These real-time applications require much lower latency in the network (≤10 ms) than the audio transmission latency. Such networks are termed low-latency networks and need higher access speeds (Koucheryavy, Paramonov & Al-Naggar, 2013). This fact led to a change in the structure and the way of building the network.

The next step in the evolution of network latency involves the concept of tactile information. In simple words, human senses will be transmitted over the Internet. In this case, the latency of transmitting information within the network must be ≤1 ms because this time is sufficient

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for a "true sensation" since the human body response time under tactile stimulation is measured at 0.15-0.8 s (Fettweis *et al.*, 2014; Jastrebova, Vybornova & Kirichek, 2016). Then, why do the senses need to be transferred? The following example will emphasize the importance of why senses need to be transferred. For example, you want to buy a coat from an online store. If we could feel the material and, possibly, try on the coat with the assistance of virtual reality technology combined with the Internet transmitting tactile information, we could avoid dissatisfaction. This example is one of the countless examples to emphasize the benefits of the new Internet generation – TI or Internet with ultra-low latency (Citrin *et al.*, 2003; Grohmann, Spangenberg & Sprott, 2007; Dohler *et al.*, 2017; Zhang, Liu & Zhao, 2018). Table 1 below shows the requirements for latency and access speed of different network generations (Koucheryavy & Vybornova, 2016).

Table 1. The value of latency and access speed required for different types of networks

Network	Required latency	Required access speed
NGN	100 ms	in the order of tens or hundreds Mbps
Low-latency network (Medical Network)	10 ms	in the order of several hundred Gbps
Ultra-low latency network (Tactile Internet)	1 ms	in the order of Tbps

1.2. The Tactile Internet concept

According to ITU (Fettweis *et al.*, 2014), the TI is an ultra-low latency Internet, with short data transmission time, high availability, reliability, and security. It would create a significant impact on the economy and society by bringing new opportunities for the emerging technology market and providing essential services, especially in the Industrial Revolution era 4.0 (Wollschlaeger, Sauter & Jasperneite, 2017). According to IEEE P1918.1 (Aijaz *et al.*, 2018), the TI is a network or a network of networks for remotely accessing, perceiving, manipulating or controlling real and virtual objects or processes perceived in real time. The TI allows us to interact with objects in the environment at tactile latency, for example, the response speed of the senses. Nowadays, communication technologies are widely used to move content(s) from one device to another. Content can be multimedia or data. Unlike the conventional Internet, the TI allows us to transmit the tactile (touch, contact) as well as the stimulation and the control via the Internet in real time. Not only the content needs to be transported, but the tactile information is now also transmitted. The senses allow people to perceive their surroundings and decide whether or not to adapt themselves or adjust the environment accordingly. This cognitive process limits the speed of our interaction with the situation. Therefore, to interact with a technical system naturally and intuitively, the feedback of the system must be adapted to the human responding time. For this reason, the TI requires an end-to-end delay of ≤1 ms. However, with the existing network infrastructure and technologies, it is challenging to meet this requirement or "1-millisecond challenge" (Bachhuber & Steinbach, 2017). In conclusion, some of the TI features could be summarized as follows:

- Latency: less than 1 ms;
- Reliability: to perform critical tasks (for example, remote operation), network losses, equipment failure, etc. are unacceptable;
- High data transfer rate: more than 10 Gbps;
- High network density: to support the connection of more than 100 devices per 1 square metre.

The rest of this paper is organized as follows: Section 2 reviews the "1-millisecond challenge" and the importance of technical requirements. Section 3 introduces the reference architecture of the TI. Section 4 will focus on a discussion of the emerging technologies towards the TI. Section 5 considers the relationship between the TI and the Internet of Skills, as well as Haptic Communication. TI applications will be discussed in detail in Section 6. In Section 7, TI standards are presented. Finally, Section 8 provides a conclusion for this paper.

2. The "1-millisecond challenge" and Technical Requirements

There are many challenges and technical requirements in making the TI into reality, such as ultra-low latency, ultra-reliable connectivity, safety, appropriate codecs, etc. This section will investigate these challenges.

2.1. The "1-millisecond challenge"

The most critical requirement of the TI, which will shape the design of future networks, is 1 ms latency (Jiang *et al.*, 2019). It helps to experience real-time interaction with the environment (Varsha & Shashikala, 2017). Otherwise, poor coordination of the digital responses of the senses will cause misconceptions. For example, if the eyes perceive a movement, which is slightly delayed compared to what is perceived by the vestibular system while the rest of our body remains static, this delay leads to "cybersickness" (Burdea & Coiffet, 2003; LaViola, 2000). This fact is vital for machine-type communication that enables real-time automation and control of dynamic processes in industry, manufacturing, traffic management, etc. (Simsek *et al.*, 2016a).

Currently, the latency in wireless network standards has been significantly improved. For instance, in LTE technology, end-to-end latency could reach to 10-25 ms (Ericsson, 2013) and fully meet the requirements of real-time games. However, it is still far away from the 1-millisecond requirement of the TI. The leading cause of latency in the wireless environment

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is fading; but generally, in a network of the TI context, end-to-end latency consists of the following factors:

- The time to transmit the information from the sensor (or from the person in the case of tactile interactions) through the communication infrastructure to a control server;
- The time for the information to be processed and generate a response;
- The time to pass the response back to the original subject (e.g., human) through the network infrastructure.

If this latency exceeds the response time of the human body, the user experience is less realistic due to the considerable distance between the stimulus and the response received. Figure 1 shows the assumed latency for components in the TI network (Cakuli, 2016).

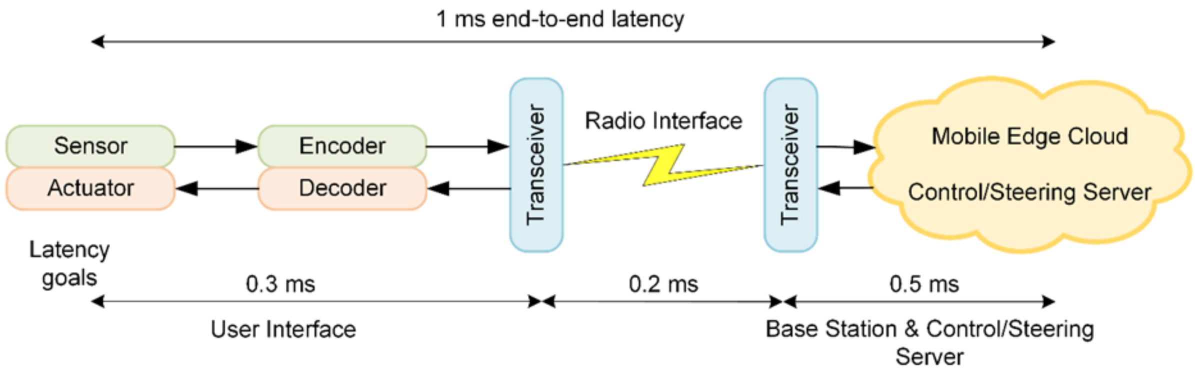

Figure 1. The assumed latency for components in the TI

Notwithstanding, the 1 ms latency requirement is an enormous challenge. The physical transmission must have tiny packets to enable one-way physical layer transmission of 100 μs. To achieve that value, the packet duration must not exceed 33 μs (Fettweis, 2014) so that the processes of encoding/detecting/decoding of the packet at the transmitter/receiver would not result in additional latencies. This fact limits the packet size to less than one-third of the target latency. The modulation used in current LTE systems is not the right choice for the TI; since the duration of one OFDM (Orthogonal Frequency Division Multiplexing) symbol alone is close to 70 μs long (Fettweis, 2014). Current systems and mobile network technologies cannot meet this requirement because their protocols demand too much overhead for connectivity management, synchronization, channel resource allocation, as well as mobility. Thus, a new wireless technology standard (5G) far beyond 4G LTE technology is needed (Li *et al.*, 2019; Durisi, Koch & Popovski, 2016).

2.2. The ultra-reliable connectivity requirement

Another essential specification of the TI is reliability or ultra-reliable connectivity (Aijaz, 2016; Bennis, Debbah & Poor, 2018). It means reliability is quantified as seven nines reliability: i.e., an outage probability of 10^{-7} (milliseconds of outage per day) (Fettweis, 2014; Yilmaz *et al.*, 2015). It is fundamental to keep the packet loss to a minimum, especially in wireless environments that are prone to errors. Again, the next 5G generation wireless technology, which is designed for ultra-reliable connectivity, will be a significant foundation, all credit to the TI that establishes connectivity.

2.3. The safety requirement

The next difficulty is to provide security as well as to improve the safety of the TI and its applications. This fact is noticeable because the uses of the TI will spread from large-scale industrial systems to daily infrastructure or services. Therefore, it could be harmful if it does not operate properly. With the stringent latency requirement, security must be embedded in the physical transmission and ideally be of low computational overhead (Simsek *et al.*, 2016a). New techniques and secure ways need to be developed to ensure that only legitimate receivers can process the information, and it requires new, reliable, and low-delay methods. Advanced trust models, security for new service delivery models, and a broad range of infrastructure are dependent on new technologies, and increased privacy concerns are expected. It can be said that security is a complex issue. It depends on many factors, which should be carefully controlled during communication over the TI (Li *et al.*, 2019; Szymanski, 2017).

2.4. The codec's requirement

Besides, tactile information also should be handled similarly to audio and video information. An essential technological aspect in this context is the acquisition, compression, transmission, and display of haptic information with minimum latency (Steinbach *et al.*, 2019). That means a need for separating the codecs for tactile applications to handle the compression of haptic information and to provide transmission of tactile data. These codecs will be the decisive factor for TI's scalability (Chaudhari *et al.*, 2015); however, it has received comparatively little attention so far.

3. Architecture

Architectural design for the TI requires compliance with many stringent requirements. The architecture needs to have some essential features:

- It can be mapped to various TI applications;
- It can support a diverse range of connectivity from local to broad areas via wireless (5G network) or hybrid networks;
- It should have a modular design, which is suitable and flexible for implementing other network technologies, which help to separate the control and data planes or to take advantage of computing resources from clouds;
- It must have the ability to integrate and interact with third-party products and services;
- It should have efficient resource management.

In addition, because the TI allows transmitting actuation and touching in real-time as well as transmitting haptic and non-haptic control via the Internet, there is a difference compared to auditory and visual senses. Touch should be sensed by imposing a motion on an environment and feeling the environment by a distortion or reaction force (Steinbach *et al.*, 2012). Therefore, the sense of touch occurs bilaterally. It means that haptic feedback needs to close a global control loop (Figure 2), while, in the case of non-haptic feedback, there is no need for the control loop.

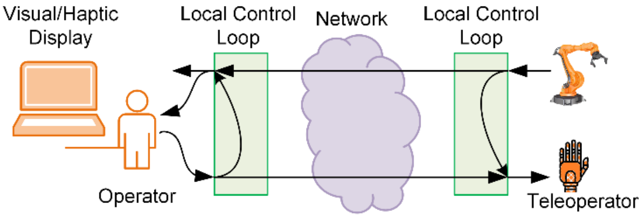

Figure 2. A closed control loop in case of haptic feedback

According to the IEEE P1918.1 standard working group (IEEE 1918.1), the reference architecture of the TI includes three domains: a controller/master domain, a network domain, and a controlled/slave domain. Figure 3 below presents the reference architecture of the TI that includes these three domains.

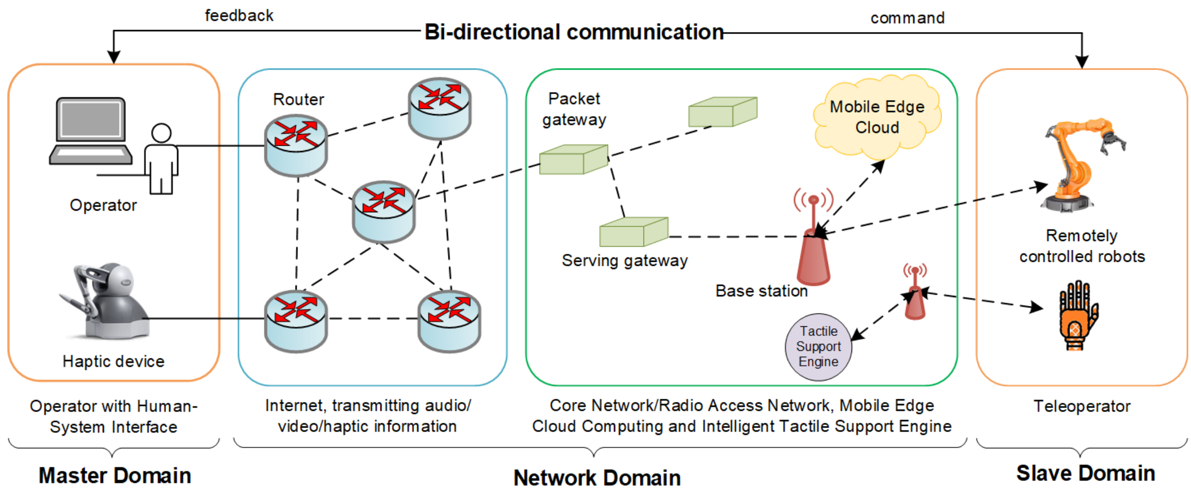

Figure 3. End-to-end reference architecture of TI (Dohler *et al.*, 2017; IEEE 1918.1)

3.1. Master Domain

In the case of remote operation and HC, the master domain includes an operator (human) with tactile Human System Interface (HSI). This system (usually a haptic device, robotic arm, etc.) will convert human input into tactile input via different coding techniques. The user can touch, manipulate, and feel objects in real and virtual environments. The master domain primarily controls the operation of the slave domain, which will be discussed later, through command signals. The master domain also supports audio and video feedback, which not only enables remote operation and non-haptic control but also enhances perception. The networked control systems provide commands to the sensor and actuator system (Aijaz, 2016).

3.2. Slave Domain

As for HC, the slave domain includes a controlled robot (teleoperator) controlled by the master domain through command signals. The teleoperator interacts with the environment and sends haptic feedback using the reverse path. Energy exchanges between the slave and master domains to create a closed control loop through feedback and command signals. The networked control systems also contain sensor and actuator systems in the slave domain. The actuators manipulate the system, whereas the sensors monitor the system and environment.

3.3. Network Domain

The network domain acts as the medium for bilateral communication between the master and slave domains. It consists of network devices such as routers and gateways. The router directs the haptic input (in the form of small packets) to the gateways (e.g., packet gateways, serving gateways). Then the data will be sent to the base stations and communicate with the tactile supported infrastructure and pass to the destination robot in the slave domain. Due to the strict requirements of reliable and responsive connectivity, which determines latencies for real-time control and remote operation, the infrastructure, as well as network technologies in the domain, needs special attention. Besides the 5G communication, new emerging network technologies such as Software Defined Networking (SDN), Network Function Virtualization (NFV), and Mobile Edge Cloud (MEC) should be developed and applied to the TI infrastructure (Antonakoglou *et al.*, 2018; Van Den Berg *et al.*, 2017).

4. Emerging Technologies towards Tactile Internet

The analysis above indicated the redesign of network infrastructure and the implementation of new technologies to serve the TI are necessary. Although some studies (Ateya *et al.*, 2018b) focus on the development of intelligent core networks, capable passive optical LAN (Wong, Dias & Ruan, 2016) or wireless body area networks (WBANs) (Ruan, Dias & Wong, 2017) for the TI, it could be stated that the fifth generation of mobile communications systems will underpin this next Internet generation (Simsek *et al.*, 2016b). This section will dissect parts of the emerging technologies, and their combination will be the lever for the establishment and the development of the TI soon (Bojkovic, Bakmaz & Bakmaz, 2017).

4.1. 5G, Network Slicing, and physical layer technologies

Now the 4G mobile communication systems cannot meet the technical requirements of the TI. Therefore, the next 5G mobile communications systems are expected to fulfill the wireless communication requirements (Marcus, 2015) and act as the foundation for the TI at the wireless edge due to the overlapping features of ultra-low latency, high reliability, and security in communication between 5G and TI (Maier *et al.*, 2016; Jiang & Liu, 2016; Sachs *et al.*, 2019; Mountaser, Mahmoodi & Simeone, 2018; Liu *et al.*, 2018b). In general, the introduction of 5G supports the evolution of traditional mobile communication services. It also addresses different uses such as machine-type communication, sensor networking, healthcare, industrial automation, education, smart grids, smart energy networks, and vehicular communication in intelligent transport systems, etc.

According to the prediction of the Cisco Visual Networking Index (VNI) (Cisco VNI, 2016-2021), by 2021, 5G will be 0.2 percent of connections (25 million), but 1.5 percent of total traffic.

Besides, to meet the tremendous growth in connectivity, the density of devices, and a massive increase in traffic in the future, additional spectrum must be allocated to the 5G wireless access. Moreover, to enable high data rates (≥10 Gbps) and high capacity in the 5G network, the millimetre-wave range is consequently relevant (Rappaport *et al.*, 2013; Niu *et al.*, 2015). With massive bandwidth in the band from 30 GHz to 300 GHz, mmWave communications have been proposed to be an essential part of the 5G mobile network to provide multi-gigabit communication services, such as high definition television (HDTV) and ultra-high-definition video (UHDV). Since 5G needs to satisfy the stringent requirements for latency, reliability, connectivity, mobility, and security in the TI (Andrews *et al.*, 2014), the architecture of 5G needs to be flexible and optimized to take advantage of network resources. In particular, it should use modular network functions, which can be deployed and scaled on demand. In other words, 5G should be designed so that different vertical applications can efficiently share a common physical infrastructure. It can be done through the abstraction of 5G networks (e.g., network slicing). The network slice can be considered as a group of network functions that work together with a specific radio access technology to achieve the purpose of the network (Simsek *et al.*, 2017).

In this case, network slices would be designated to differentiate vertical application sectors (Foukas *et al.*, 2017; Zhang *et al.*, 2017a; Rost *et al.*, 2017; Ordonez-Lucena *et al.*, 2017; Shafigh, Glisic & Lorenzo, 2017; D'Ursol *et al.*, 2018; NGMN Alliance, 2015). The 5G slice intends to provide the traffic treatment necessary for its function. A new service can be deployed and tested in a slice without affecting the running services of other slices. The flexibility behind the slice concept expands the existing businesses and creates new businesses. Such envisioned network slicing can be achieved through SDN and NFV (Zhang *et al.*, 2017b), which will be presented in the next sections.

Many communication techniques for the TI services have been developed (Kim *et al.*, 2019), and a lot of companies in the ICT field are engaged in this field to implement the concept of the TI. Specifically, Huawei has recently developed many technologies, such as SCMA, F-OFDM, and polar code, to achieve high speeds and low network delays; each of them will be further considered separately (Huawei, 2015).

Filtered-OFDM (F-OFDM) is a modernized OFDM technology. It is partitioning into sub-carrier spacing and organizing in such a way that a particular set of parameters will be used for each task. It makes the signal processing more accurate, faster, and less energy-intensive. F-OFDM will support various waveforms and multiple access schemes for different application/service scenarios. The first results of the planned testing showed that F-OFDM increases the overall system throughput by 10% due to the use of free protected bands in the LTE system. F-OFDM also sustains the asynchronous transfer of data from various users; thereby throughput of the system increases to 100% in comparison with the LTE system in the transmission of several types of traffic (Jastrebova, Vybornova & Kirichek, 2016).

Sparse Code Multiple Access (SCMA) technology is a multi-station access technology based on sparse codes. It allows the combination of OFDMA technology with CDMA code to provide broader access for devices. This non-orthogonal technology was explicitly developed for possible usage in the fifth-generation networks (Lu *et al.*, 2015; Nikopour & Baligh, 2013). The idea is to improve the spectral efficiency of wireless radio access. SCMA encodes binary data streams directly to multi-dimensional codewords. Each codeword represents one of the distributed transmission layers. The codeword is selected from the SCMA codebooks for any level. Similarly, coded bits in SCMA are directly mapped to multi-dimensional sparse codewords selected from layer-specific SCMA codebooks. It allows several data streams to share the same time-frequency resources of the OFDMA signal. The technology provides a more flexible and efficient adaptive mechanism, increases throughput, reduces transmission delays, and saves electricity. The test results indicated that this technology increases the throughput for the downstream channel by 80%, and it increases the number of connected devices by 300% (Jastrebova, Vybornova & Kirichek, 2016).

Polar Code is proven to reach the Shannon channel capacity by using encoders and sequential cancellation decoders (Huawei, 2015). It is one of the best technologies for encoding with direct error correction. Their test outcomes revealed that the polar code outperforms the turbo code used in the LTE system, especially for short code length. Furthermore, under certain conditions, a peak speed of 27 Gbps was achieved in the descending mode.

Multi-User Shared Access (MUSA) (Yuan, Yu & Li, 2015) is a multiple access solution offered by ZTE (Yuan *et al.*, 2016) based on discharged codes. It allows multiple access in networks with a high load without the need for network planning. It significantly increases the number of connected devices to the system, as well as improves the overall coverage. As a consequence, it demonstrated an increase in capacity by 200% compared to the networks of the previous generation (Jastrebova, Vybornova & Kirichek, 2016).

Also, the Massive-MIMO technology, which can simultaneously accommodate many co-channel users (Swindlehurst *et al.*, 2014), as well as the Full-Duplex technique (Zhang *et al.*, 2015), which can transmit and receive at the same time on the same frequency, are becoming the most promising ingredients of the emerging 5G technology.

4.2. SDN – Software Defined Networking

SDN technology provides a powerful solution for the challenges in the 5G network and the TI system, especially the "1-millisecond challenge". SDN is an architectural framework formed by decoupling the control plane and the data plane. SDN (Kreutz *et al.*, 2015; Farhady, Lee & Nakao, 2015) enables direct programmability of network control through software-based centralized controllers.

The control and data planes communicate with each other through an open standard interface protocol such as OpenFlow protocol (Athmiya, Shobba & Sarimela, 2016). Due to its centralized nature, the controller can get a global view of the network. It helps the network administrators to adjust the network traffic flow dynamically, facilitate low-latency forwarding path discovery, reliable multipath routing (path optimization based on the application requirements), and network virtualization (Mahmoodi & Seetharaman, 2014; Morales, Aijaz & Mahmoodi, 2015; Kim & Feamster, 2013; Farhoudi *et al.*, 2017; Girish & Rao, 2016). Nonetheless, additional TI research is needed because the most crucial goal is to find the path with the lowest delay while considering the rapid change of network conditions (Van Den Berg *et al.*, 2017). Besides, SDN enables the dynamic provisioning of network resources and functionalities. Hence, the network slicing can be flexibly configured (in terms of security mechanisms, network topology, management policy, etc.) with guaranteed Quality of Service (QoS). In another study (Szabo *et al.*, 2015), the authors show that packet retransmission and latency can be significantly reduced by combining SDN and network coding. As a result, SDN is one of the most critical components of the fifth-generation network.

4.3. NFV – Network Function Virtualization

Today, network services such as caching and load balancing are typically dedicated hardware (middleboxes). Their deployment and maintenance are usually complicated and inefficient. Network Function Virtualization (NFV) shifts middlebox processing from hardware to software, which can be quickly deployed in the network. In other words, NFV provides virtualization and softwarization for network functions. Therefore, it significantly decreases the dependency on hardware and results in increases in the reliability and scalability of the network (Joshi & Benson, 2016; Han *et al.*, 2015; Mijumbi *et al.*, 2016; Li & Chen, 2015). The

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resources can be easily shared among different network functions and by NFV. The numerous network functions are managed as software modules, which can be deployed in different locations of the network such as network nodes, end-node of the network edge, and data centres (Li & Chen, 2015). NFV can transfer those functions across the network to optimize the performance of the service, especially in terms of latency (Giannoulakis *et al.*, 2014). At present, the market of NFV includes switching elements (Broadband Network Gateway and Router), network appliances, network services, and applications. NFV also supports the coexistence of multi-tenancy of network and service functions by allowing the practice of a physical platform for different applications, tenants, and services. Therefore, NFV has many advantages, such as high flexibility, scalability, low cost, security, and location independence.

Particularly, NFV will adequately control the network functions, and SDN will manage the physical communication infrastructure (e.g., switches, network links, and even path management). The combination of NFV and SDN offers a method to actualize the fundamental concept of network slicing. It guarantees the closing of the loop in the TI applications, assures low latency, dynamically handles the traffic taking account of the network conditions, and accommodates a wide range of heterogeneous services with stringent QoS.

In a recent study (Ateya *et al.*, 2018b), the authors combined SDN, NFV, and Mobile Edge Cloud (MEC) into multi-levels for the core of the cellular network. The obtained result shows that this combination may support one another to solve the 1-ms problem. MEC will be further discussed in the next section.

4.4. MEC – Mobile Edge Cloud

Given the speed of light (approximately 300,000 km/s), the distance for transmission within 1 ms can be no greater than 300 km. In the case of the TI, that is the maximum distance over which the loop of tactile application can be accomplished with the assumption that there are no latencies in the communication path. This fact also means the distance between the steering and control server from the point of tactile interaction by the users should be less than 150 km (Varsha & Shashikala, 2017). Yet, considering the signal processing, switching latency, protocol handling, and impact from the air environment, the TI servers need to be placed closer to the base stations, if not integrated into the same equipment. This requirement leads to the concept of MEC, which is being standardized by ETSI Industry Specification Group (ISG) (Hu *et al.*, 2015). MEC has a robust computing capability (cloud-computing capabilities), and it is often used to handle critical requests at the edge of the mobile network and thereby dramatically reduces the latency of the process. Likewise, it provides a higher system bandwidth and reduces network congestion by providing a way for offloading data (Liu *et al.*, 2018a).

By adding some decision-making services, MEC manages traffic at the mobile edge instead of forwarding it to the remote data centres. When packets do not go through the core network to the remote data centres, the real-time services can be provided with low end-to-end latency (Ateya *et al.*, 2018a). In like manner, the TI applications can be supported if MEC architecture eliminates the considerable delay in processing. It leads to a requirement for the decentralization of services, which in turn should change the network architecture.

The architecture of a network with ultra-low delays is suggested for the implementation of the TI services (Maier *et al.*, 2016). This architecture assumes the decentralization of cloud computing in the TI networks. Figure 4 shows the traditional architecture of the IoT networks, in which several fields of IoT devices are associated with a cloud system (in this case, individual for each field).

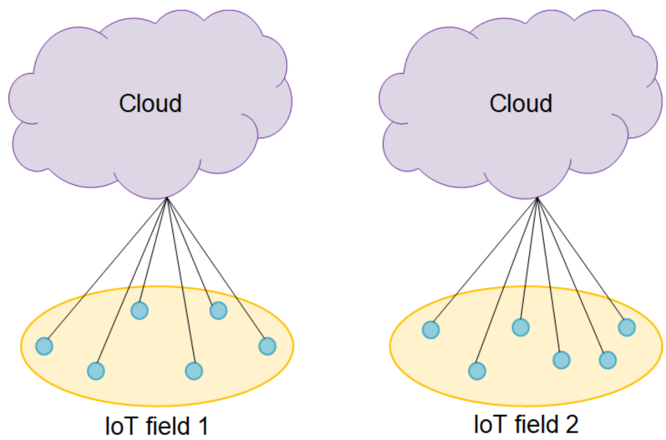

Figure 4. The traditional architecture of the IoT network

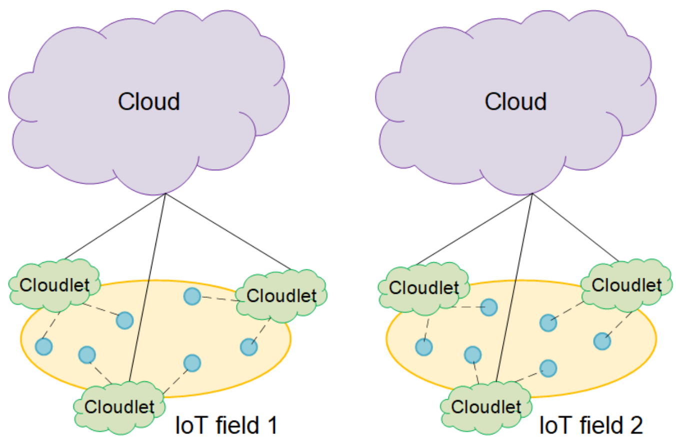

Figure 5. The decentralized architecture for realizing the TI services

When traditional architecture is used to implement TI services, delays in transmission of information between the IoT and the cloud will frequently be too large to provide the necessary quality for TI services. In a decentralized architecture, the practice of resources distributed (cloudlets) over the field of IoT devices will avoid unnecessary delays in the provision of TI services (Koucheryavy & Vybornova, 2016; Verbelen *et al.*, 2012). From a technical perspective, users take advantage of reduced communication latency and data centres take advantage of reduced overall traffic (Neaime, 2018; Oteafy & Hassanein, 2019). Figure 5 shows the assumed decentralized architecture for realizing the TI services.

4.5. Network coding

The combination of SDN and NFV provides virtualization and softwarization for networks. It also significantly reduces latency. However, to meet the 1 ms requirement in the TI, there is a need to incorporate other technologies. One of those technologies is network coding, also known as new coding strategies. It is necessary because, in the application of existing coding strategies, such as Reed-Solomon and Raptor (Fragouli & Soljanin, 2008; Wicker & Bhargava, 1994) (which are only end-to-end based), the network nodes cannot self-evaluate or change based on the network situation. By contrast, network coding permits the network node dynamically and adaptively to change the coding strategies depending on the current condition of the network (Szabo *et al.*, 2015). The most prominent network coding now is Random Linear Network Coding (RLNC) (Ho *et al.*, 2006) that supports a sliding window approach and does not work on blocks of packets. Therefore, it would decrease the delay of any communication.

Nevertheless, when using network coding, nodes will not only store but also compute and then forward the packets. Thus, the current situation for next-hop communication would be considered. The node will select the appropriate coding strategy. It does not deal with the losses over the whole path (end-to-end, E2E), but it just takes care of the losses between two nodes (hop-by-hop, HbH). It reduces retransmissions dramatically, so latency is also reduced (Cabrera *et al.*, 2019). The encoders, recoders, and decoders need to be allocated flexibly so that the network coding could work properly. With the appearance of SDN and NFV (encoders, recoders, and decoders are implemented as NFV), network coding promises to be a crucial technique in the 5G network. The authors in Szabo *et al.* (2015) pointed out that the combination of network coding with SDN can improve reliability and reduce the latency in the 5G system by recoding and sliding window features of network coding.

4.6. Compression methods

One of many methods to comply with the latency requirement of the TI is to use a suitable data compression method. In the ideal case, the distortion must not go beyond human perceptual thresholds. The essence of data compression is to remove irrelevant information, which either is not perceivable by the human or cannot be displayed due to hardware limitations. If the perceptual quality and system performance are not affected by the compression methods, then these methods are known as transparent (Elhajj *et al.*, 2001). It means that the correct parameters (max-level value, window-session size, etc.) are needed to compress the data and achieve the required reliability. Although there are many data reduction standards for digital audio and video (Storer, 1987; Sikora, 1997; Kimura & Latifi, 2005), these algorithms cannot be applied to tactile data, especially haptic data, because it requires a low execution time and stability (Chaudhari *et al.*, 2015; Steinbach *et al.*, 2011; Shahabi, Ortega & Kolahdouzan, 2002). Therefore, to achieve a reliable data reduction for each combination of data samples, further research is necessary.

4.7. Multiplexing different modalities

In addition to transmitting haptic data in the TI, there is still a need to transmit both audio and video to provide synchronization of all media forms. Combining multiple data types or multiplexing will increase perceptual performance; thus, it would meet TI requirements. Because each data type has different requirements, such as frequency, priority, latency, or transmission rates, an adaptive multiplexing model is needed to encode data from different streams (Al Jaafreh *et al.*, 2018). Moreover, large video packets can affect or block haptic packets. This fact leads to latency and jitter violation. A few approaches give the haptic data the highest priority (Cizmeci *et al.*, 2014), but, in reality, this is not efficient due to protocol header overhead when transmitting small packets with a high rate (Cizmeci *et al.*, 2017). Besides, different error control schemes and congestion controls need to be considered when applying the multiplexing system.

In Eid, Cha & El Saddik (2011), the authors proposed to use ADMUX multiplexer with compression and control methods to improve the service quality of communication. In Yuan, Ghinea & Muntean (2015), Adaptive Mulsemedia Delivery Solution (ADAMS) multiplexer was proposed based on a client-server architecture. It permits adaptively controlling the transmission rate of different streams regarding the human perception limits. Then again, it does not cooperate with the security mechanisms. Overall, the current works in the field of multiplexing the haptic data with audio and video modalities are limited, making it an open challenge.

4.8. Cloud robotics

With recent advancements in robotic development environments, robots become more prevalent in everyday human activities, especially in the health care field (assisting the elderly, people with disabilities, remote surgery, etc.). For the TI, robots provide three main functions: sensation, actuation, and control (Kamei *et al.*, 2012). However, standalone robotic services are not enough to support countless daily tasks and medical-related activities, which require multi-robot systems with many functionalities. In fact, stand-alone robots, sensors, and humans should collaborate and communicate with each other via a network to create networked robots (Sanfeliu, Hagita & Saffiotti, 2008). Similarly, some technological issues should be considered when providing robotic services: multi-robot management (e.g., classify abilities and allocate appropriate robots depending on the services); service coordination management (e.g., the state of each location must be monitored to execute the service in proper situations); multi-area management (e.g., dynamic location information of users, robots, and target objects should be shared); user attribute management (e.g., appropriate robots should be chosen by referring to the user information). Cloud robotic solution provides robotic services continuously and seamlessly through distributed task coordination at various locations and will become a critical element in the TI (Huaimin *et al.*, 2018). Cloud robotics will abstract robotic devices and provide the means for utilizing multi-robot systems as a cloud of robots to support task offloading and share computation resources, information, and data in robot applications (Kamei *et al.*, 2012; Hu, Tay & Wen, 2012; Kehoe *et al.*, 2015). Likewise, it offers access to new skills and knowledge, which are not learned by robots through IoS (Dohler *et al.*, 2017). Cloud robotics takes advantage of machine-to-machine (M2M) for the communication between robots, and machine-to-cloud (M2C) for the communication between robots and remote cloud (Hu, Tay & Wen, 2012). Yet, cloud robotics introduces new challenges in privacy and security because robotic services are related to both the real physical world and cyberspace. If a robot is being attacked, then it could lead to significant problems due to disrupting functionality or loss of user data.

4.9. Artificial Intelligence

Artificial Intelligence (AI) (Russell & Norvig, 2009) is necessary to break the limitations and to improve safety, accuracy, and security in the TI. It also reduces congestion in the core network, thereby reducing the latency. Using intelligent algorithms, AI speeds up the action at the robot side and the reaction at the operating side. In other words, AI predicts haptic and tactile experience (Simsek *et al.*, 2016a) (the most basic prediction algorithm is a linear predictor (Hinterseer *et al.*, 2008)). The collected tactile data will improve these algorithms. To demonstrate, after the initialization and training process, the algorithms will decide whether to update training values from current real data or not. These algorithms must be able to recognize patterns, learn from false predictions, and improve over time (Van Den Berg *et al.*, 2017). For example, in the field of telesurgery, after AI engines are monitoring, learning data, and foreseeing the risks of a manipulation error due to the delayed display of video stream, these AI engines can immediately postpone the surgical operations while sending out warnings to the surgeon (Zhang, Liu & Zhao, 2018). Not to mention, if AI techniques are applied to edge cloud architectures, then it will accelerate the computing process so that the physical limitation that arises due to the finite speed of light could be overcome.

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5. Tactile Internet in Relation to Haptic Communication and Internet of Skills

As mentioned above, the TI transmits touch sensation and actuation via the Internet in real time by enabling HC (Steinbach *et al*., 2012) and supporting the IoS (Dohler *et al*., 2017). Their combination creates multiple beneficial applications in many life aspects. The HC and IoS, in relation to the TI, will be reviewed in this section.

5.1. Tactile Internet and Haptic Communication

Firstly, it is essential to distinguish the relationship between TI and HC. Similarly to the data communications that run over the conventional internet, HC is primary applications (touch, actuation, control in real time) that run over the TI. It does not mean that the TI only transmits haptic information, which requires strict latency due to the characteristics of haptic feedback. But the TI also transmits non-haptic information such as networked control signals, in which the dynamic processes for connecting sensors and actuators are involved. It should be noted that, unlike in conventional audio/video transmission, haptic information and feedback signals close a global control loop. The sense of touch occurs bilaterally, i.e., it is sensed by imposing a motion on an environment and feeling the environment by a distortion or reaction force (Aijaz *et al*., 2016).

There are two types of feedback in haptic information: kinesthetic/force perception and tactile/cutaneous perception. Kinesthetic provides information on forces, position, torque, and velocity, which are sensed by the joints, muscles, and tendons of the body. Tactile perception provides information on surface texture and friction, which are sensed by the human skin. The term “tactile” suggests the perception of touch and leads to the requirement of an ultra-low delay constraint in the TI (Fettweis & Alamouti, 2014). In HC, the sensors convert tactile parameters, like contact, location, pressure, shear, slip, vibration, and temperature, and kinesthetic perceptions, like position, orientation, and force, into electrical signals that are transmitted when the commands are executed. However, haptic signals need to be digitized and standardized to create compatible products for vendors.

Currently, the applications of HC, such as telesurgery and education (see Section 6), are synchronized with video and audio data. Anyhow, if the time interval between tactile movement and visual is greater than 1 ms, then it can cause motion sickness or other uncomfortable influences. In a virtual environment, multi-modal sensory information (e.g., combination of different types of data) plays a crucial role in enabling the participants to interact and communicate (Basdogan *et al*., 2000); especially haptic modality will enhance the experience for the users. This combination is comparable to billions of nerve cells arranged in patterns to coordinate multiple functions. The brain synthesizes information about colour and sound. Then it combines this information with shape data, which can be perceived through touch to create a complete representation of the object. The integration of haptic feedback into conventional communication will develop countless new uses in various fields. The TI creates a "paradigm shift" to deliver the content with ultra-low latency and high throughput. The most common function is haptic telepresence, which is the haptic interaction between remote objects, such as in teleoperation or telesurgery, or in hazardous environments (Steinbach *et al.*, 2019). Alternatively, a virtual reality system (see Section 6) is useful in education and remote training (Basdogan *et al.*, 2000). Haptic devices are required to facilitate these applications and support the HC. Some examples are the ultrasound panel (Hoshi *et al.*, 2010), vibro-tactile glove (Martinez *et al.*, 2011), finger (Weber *et al.*, 2016), force feedback glove, force feedback gripper, and force feedback mechanical arm (Shima & Sato, 2017). Adding to the haptic devices are the kinematic devices to capture the motion of the operator (kinematic sensors) and mimic that motion at the slave domain (see Section 3) (kinematic actuators) (Dipietro, Sabatini & Dario, 2008; Ma & Ben-Tzvi, 2015; Baldi *et al.*, 2017; Ma *et al.*, 2011; Bainbridge & Paradiso, 2011). However, the effect of delay on HC is considerable because minor latency may destabilize the haptic system. That is why HC needs TI with ultra-low latency and high-reliable connections.

5.2. Tactile Internet and Internet of Skills

The IoS concept (Dohler *et al.*, 2017) assumes the transfer of "experience" virtually, as a result of the "digitization" of physical skills. In other words, the IoS will deliver the physical experiences remotely. This concept will push the learning process to a new level and revolutionize servicing capabilities for industries. IoS, unlike the IoT and the TI, does not impose new demands on networks with ultra-high density and ultra-low latencies. But this kind of network would be fully suited for the characteristics of the TI. IoS implements new classes of services (see Section 6) to apply a "skilful" network for acquiring new skills by people and robotic devices, which eventually lead to better educational activities in general.

The two concepts, TI and IoS, were designed to complement each other. They work together as a single cyclical system, where "human skills" are primarily recorded in the master domain. Then the information is transferred to the slave domain, where the feedback (tactile response) is returned as a new set of information back to the master domain. Human skills in the master domain can be captured using the human-system interface. For example, a tactile glove translates human input data into a specific set of instructions for movements and pressing so that the robotic arm in the slave domain can follow these instructions to perform the same movements and press with a precise pressure (Kim, Dohler & Dasgupta, 2018). As soon as the hand signals are received, they are transmitted through the network infrastructure to the slave domain, in which the robotic device reproduces the received signals. The communication between the two remote domains should be fast and stable so that the master domain can accurately control and “sense” the remote environment based on the feedback signals generated by the robot in the slave domain.

The introduction of new services transforms the network into a network of intelligence, then provides the new skills training to people and robots. Ultimately, this would lead to higher labour productivity and better product quality. For these reasons, IoS, as well as IoT and TI, are essential components of the digital economy (Goldfarb & Tucker, 2017).

6. Applications

It has been about six years since Professor Gerhard P. Fettweis introduced the TI concept (Fettweis, 2014). Various technologies have been improved over the years. Besides, new technologies also appear more and more. TI implementation is increasing (Pilz *et al.*, 2016) with inventive applications that have not been discovered before. Along with TI’s existence are the appearances of HC and IoS. These three factors create a new dimension for human-machine interaction in real time.

Potential TI applications based on ultra-low, end-to-end latency are expected to extend throughout many aspects of life with positive impacts on economic, social, educational, and medical device developments. It is difficult to list all the TI applications because it is beyond a human’s imagination capabilities. This section will elaborate on some of the prominent applications that the TI brings.

6.1. Healthcare

Healthcare (E-health) is considered as the most promising application of the TI. In the past, when the Internet was first created, information and knowledge were delivered worldwide. When the TI is available now, geographical location, as well as travel expenses, will no longer be a limitation to medical services such as surgery, diagnosis, and rehabilitation. It also means that a patient in Africa can thoroughly be examined and treated by doctors in Singapore without leaving Africa. This technology will benefit patients and assist physicians along with medical providers by incorporating TI and IoS. To have a better picture, the coronavirus disease 2019 (COVID-19) is an excellent illustration. There are many cases where medical professionals are infected with the virus while taking care of sick patients. If healthcare providers could render routine medical care remotely through gestures, pictures, or animations by using tactile robots via the IoS, then medical care providers could work in a safer environment without risking their own lives (Dohler *et al.*, 2017; Lema *et al.*, 2017; Majid *et al.*, 2020).

Another scenario for the application of the IoS is remote surgery (Arata *et al.*, 2007; Miao *et al.*, 2018). The doctor (in the master domain) will control a robotic arm (in the slave domain) to send commands and receive feedback displayed on a screen (Figure 6). To ensure a successful operation, the latency in control and the feedback must be very low, and the reliability of the connection must be very high, because unreliable communication, which leads to delayed imaging or poor image resolution, will affect the efficacy of the operator's remote handling.

Similarly, telediagnosis is the next prominent TI application, especially for people from rural areas, pregnant women, or people with disabilities. Telediagnosis is defined as a diagnosis performed remotely by a healthcare provider. Then, the evaluation data collected from the machine that monitors the patients is transmitted to a linked diagnostic centre. This kind of practice will reduce the waiting time for providing specialized medical care and reduce unnecessary costs. Although telediagnostic services have been implemented previously (even in the agricultural field (Li *et al.*, 2006)), they have used only voice and video functions without any touch sensation. However, with the TI, by using tactile gloves, physicians will have a complete picture (not only audio and video information, but also haptic information is provided) to examine the condition of patients accurately.

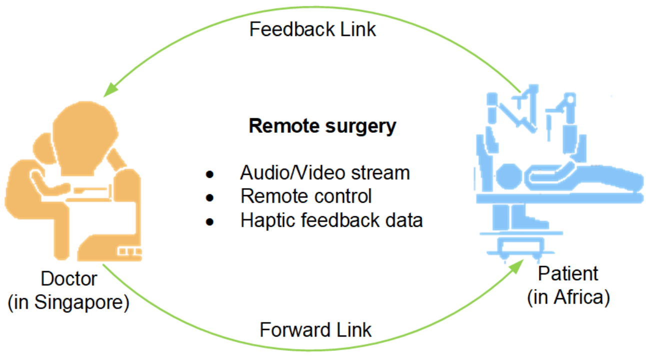

Figure 6. Remote surgery scenario

Another potential TI application in healthcare is telerehabilitation. This service will help patients who need constant care from medical workers and improve the efficiency of personalized treatment to ensure a faster recovery process. It introduces new equipment – exoskeletons (Lo & Xie, 2012) — which are attached to the limbs of the patient and controlled remotely. It reinforces the limbs to move with more force than a patient's muscles. Therefore, a patient who uses a wheelchair can walk with an exoskeleton's support. The time spent on calculating the exoskeleton reaction should be short enough so that these movements would be within the tactile delay.

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6.2. Industry and robotics

Unlike the Industrial Revolution 1 (the revolution of steam power), the Industrial Revolution 2 (the revolution of the division of labour) and the Industrial Revolution 3 (the revolution of electronic and information technology systems), the upcoming Industrial Revolution 4.0 (Wollschlaeger, Sauter & Jasperneite, 2017) will improve the production process to meet market changes quickly. This real-time revolution enables cyber-physical systems and moves toward digital transformation that includes storage, smart machines, smart factories, and exchanging information systems. It connects humans and machines and improves resource handling and coordination of processes in the manufacturing chain (Haddadin, Johannsmeir & Diaz Ledezma, 2019). Therefore, it sets out many new requirements from reliability to security in real time. The production systems and the robots in the high-tech factories are remotely controlled (industrial teleoperation) through the monitoring and control system (e.g., in construction sites or mines) (Li *et al.*, 2019). These high-tech factories (e.g., the automobile or electronic components factories) and processes (e.g., precisely controlling moving devices) have stringent requirements in latency, reliability, safety, or energy consumption, which can only be realized in the TI (Weiner *et al.*, 2014; Varghese & Tandur, 2014; Aijaz & Sooriyabandara, 2019).

6.3. Road traffic and self-driving vehicles

The transport system is a vital factor in the economy, especially in the context of smart city development. However, accidents, traffic congestion, fuel efficiency, and even air pollution problems in traffic systems cause significant losses in life and economics. New TI communication standards between vehicles, in particular the use of integrated network/control design and cloud computing (Whaiduzzaman *et al.*, 2014; Chen *et al.*, 2019), as well as the use of orthogonal heterogeneous communication technologies, will deal with the issues mentioned above (Dressler *et al.*, 2019).

In Vehicular Ad Hoc Network (VANET) (Cunha *et al.*, 2016), the vehicles and drivers need the full picture of the traffic flow and the road conditions to prevent collisions and emergencies on the road (Duc *et al.*, 2018). To meet this requirement, wireless connections should be used, because they have high reliability, the ability to support multiple connections at the same time, and especially ultra-low latency (in the order of 1 ms). Again, these requirements can only be met in TI based on 5G connections.

Some cases benefit from the network generation with super-low latency as follows:

- Emergency vehicles (e.g., ambulance, police cars, firefighting vehicles, etc.);
- Avoiding hidden objects and obstacles (She & Yang, 2016);
- Self-driving vehicles (Amadeo, Campolo & Molinaro, 2012; Lee *et al.*, 2002).

6.4. Virtual Reality, Augmented Reality and gaming

Virtual Reality (VR) and Augmented Reality (AR) are drawing more and more attention from researchers as well as industry. VR is defined as a completely virtual environment, where the users interact with the virtual objects. In other words, VR immerses users into the virtual environment. VR applications are useful in future education and gaming applications. By combining with HC, VR creates a haptic virtual world and allows multiple users to interact with each other physically via a simulation tool. For example, users can feel the impact of being attacked when playing a video game through haptic feedback. That makes the experience lifelike.

On the other hand, augmented reality combines virtual and real objects in a physical environment. An AR application visualizes the dynamic content and displays an augmented view of a real object in real time. These applications are more useful in assistance systems such as driver-assistance systems, medicine, maintenance, or education. The content is no longer static but becomes more dynamic. The combination of VR, AR, and haptic devices promises to produce many application scenarios in the film, gaming, and mobile industries (Repperger & Phillips, 2006).

Yet, some technical challenges must be solved to facilitate the implementation of these applications. Specifically, a high level of precision or high-fidelity interaction in VR requires low-latency, high-throughput and reliable communication (Elbamby *et al.*, 2018) to transmit the movements of the users to the VR server for processing. Then, the results are returned to the users in the form of haptic feedback. The players' experience in real-time gaming also requires low end-to-end latency because the delay impacts the synchronization between multiple players (so-called lag) and the perceived realism of the game directly. The TI can solve all problems encountered in VR, AR, and gaming with virtualization and computing technologies (Braun *et al.*, 2017; Sukhmani *et al.*, 2019).

6.5. Education and sports

The TI would establish multiple beneficial applications in the educational field based on haptic interaction in combination with virtual and augmented reality. Distance learning becomes more popular and effective through virtual environments with multimedia and haptic feedback. Not only knowledge but also skills will be conveyed to the learners with the support of the IoS. Through the TI, students experience real-time activities anywhere, any time with all kinds of senses by performing a manual operation on a virtual object, and the instructors guide or correct their students if necessary. The instructor's physical presence is not needed any more (Yorita *et al.*, 2009). Such activity requires multi-modal human-to-machine communication, which is only possible if the latency is extremely low, and the network throughput is high.

Another useful application for individuals with speech disabilities is tactile gloves that convert the hand's movements (sign language) into speech (sound) by using fast streaming encoded data (Cakuli, 2016).

Many coaches for swimming, skiing, and figure skating found it difficult to capture athletes' performances comprehensively through visual contact or typical communication methods. The athletes use a tactile wearable training suit or bracelet to provide feedback about speed, position, posture, and endurance to their coaches. Then, the coaches can give commands or train the athletes in a real-time manner (Spelmezan, 2012; Shull & Damian, 2015; Umek, Tomažič & Kos, 2015; Bermejo & Hui, 2017). This real-time interaction is impossible without ultra-low latency. Besides, the information feedback collected can be stored and handled by other smart systems to get the individual top-level performance.

6.6. Energy and smart grids

In recent years, due to high electricity demand, the electricity industry tends to shift from a centralized system to a decentralized system. In that context, smart grids (Fang *et al.*, 2012) emerged as a potential solution to control power production, distribution, and transport based on advanced communication technologies (Gao *et al.*, 2012; Tuballa & Abundo, 2016). The TI and 5G provide more reliable, high-speed communications through human-to-machine interaction (Maier, Ebrahimzadeh & Chowdhury, 2018), then they can be applied in smart grids to meet the strict requirements (Faheem *et al.*, 2018). Smart meters (the consumer side) and intelligent monitors (the company side) (Siano, 2014) can be used to automate energy distribution and optimize power consumption based on two-way communication using wireless connections with low latency and high throughput over the TI.

Another benefit of the low latency of communications between local suppliers is the synchronization of co-phases of power suppliers. It is necessary because the system needs to minimize reactive power and dynamically control status (on/off) of suppliers within a small angle of phase (Fettweis, 2014).

6.7. Online shopping and E-commerce

As was illustrated in Section 1, the TI brings a new experience to the users (touch and feel objects) for the online shopping experience. It invents countless business opportunities for consumers, application developers, businesses, and telecommunication companies, and also leads to a big jump in the product sales industry.

7. Standardization and Contributions

The TI has been studied in the last six years and its deployment is still limited. The involvement of different organizations in the development of the TI is also limited. The reason for that limitation is the lack of common standards to ensure that the products and services are used securely, reliably, and interactively. In other words, standardization is critical to end-users. Thanks to standardization, new technologies will attract a lot of attention from technology companies and quickly be introduced to the market.

Currently, various standardization bodies focus on the TI based on the technology watch report by ITU in 2014 (Fettweis, 2014) and work item on IPv6-based TI by ETSI IP6 ISG (ETSI, 2017). Among them, the emerging IEEE P1918.1 standard working group (created in March 2016) (IEEE P1918.1) defines a framework for the TI. This framework includes definitions, terminology, architecture, reference models, and application scenarios. It mainly focuses on three main areas: reference architecture (see Section 3), haptic codecs, and use cases. In addition, the standards for 5G (e.g., 5G New Radio (NR) specification by 3GPP) are also necessary for the standardization process of the TI.

This standardization process requires a coordination of the alliance groups and the collaboration of different companies to have a joint agreement on product specifications. Up to the present time, the researchers can expect positive contributions from:

- 3GPP: for 5G standardization, which is the foundation for the development of the TI. Some important documents released by 3GPP (Cakuli, 2016) are: TR 22.862 (requirements for communications in the context of 5G); TR 22.864 (network functionality, network slicing, and services); TR 23.714 (architectural design for Core Network); TR 32.842 (management of virtualized networks); TR 38.913 (requirements for next-generation access technologies).
- ETSI: for SDN and NFV to separate hardware and software or softwarization of network functionalities. In addition, ETSI also focuses on researching the Mobile Edge Cloud and routing techniques to minimize latency.
- ITU: focusing on supporting flexible networks, which meet the end-to-end QoS requirements; studies mobile front haul and backhaul to handle the bandwidth; and network softwarization.
- IEEE: focusing on standardizing building blocks of 5G, creating working groups for the TI, such as IEEE P1918.1.1 for codecs, IEEE P1918.1.2 for AI in TI, and IEEE P1918.1.3 for MAC & PHY.

8. Conclusion

The development of new telecommunication technologies has led to the emergence of communication networks with low, and then ultra-low, latencies. The networks with ultra-low latency allow the transmission of tactile data via the Internet. Therefore, the new concept of the next generation of the Internet is called TI. Nevertheless, the introduction of the TI produced a significant challenge – "1-millisecond challenge". The study of this challenge and the technical aspects related to this issue are the concern of this paper.

We have reviewed the reference architecture, which is believed to be compatible with the TI. This architecture consists of three domains: the master domain, the slave domain, and the network domain. This piece of work also pointed out that, in order to provide TI services to users, the network should be decentralized.

In this article, emerging technologies, which support the TI to solve the "1-millisecond challenge", were reviewed. The combination of network slicing in 5G networks with SDN and NFV promises a high degree of flexibility, reliability, and a significant reduction in latency, which forms the basis of TI's growth. Other technologies, such as artificial intelligence, cloud computing, or AR and VR technologies, will also be used to increase the efficiency and diversity of TI applications. The TI, with the coexistence of human senses in the real/virtual worlds, will be widely used in various aspects of life, ranging from healthcare and education to energy and e-commerce.

Equally importantly, this paper also considered and clarified the relationship between TI with HC and IoS. Their relationship is emerging and prominent in the near future. Finally, this article reviewed the active contributions of organizations and companies in the development of TI, which is the foundation for creating standards for the "TI ecosystem".

There are many future research directions for the TI. We can list some directions as follows:

- Applying machine learning and artificial intelligence algorithms to make communication intelligent for the future tactile internet (Mondal, Ruan & Wong, 2020);
- Using cognitive radio technologies to achieve quality of service without compromising delay (Farhang & Bizaki, 2020);
- Blockchain techniques may be one of the many other solutions for supporting security and privacy in the future tactile internet (Yu, Wang & Zhu, 2019);
- Redesigning protocols on different layers to guarantee 1-ms latency (Yu *et al.*, 2020).

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