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The 5G-Enabled Tactile Internet: Applications, Requirements, and Architecture

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***Abstract*—Powered by next generation mobile networking capabilities, the Tactile Internet will be able to transport touch and actuation in real-time. Enabled by suitable robotics and haptics equipment at the edges, and an unprecedented communications network, the Tactile Internet will provide a true paradigm in creating skill-set delivery networks. The fifth generation (5G) mobile communications systems will underpin this emerging Internet at the wireless edge. This paper presents the most important technology concepts which lay at the intersection of the larger Tactile Internet and the emerging 5G systems. Specifically, the paper presents some of the most important Tactile Internet applications, outlines the key technical requirements, and covers end-to-end architectural aspects of the Tactile Internet.**

***Index Terms*—Tactile Internet, haptic communications, ultra-low latency, ultra-high reliability, 5G.**

I. Introduction

Mobile communication has become an indispensable component of present day life. It continues to play an important role in modern economy, including consumer, health, education, logistics, and other major industries. Mobile communications networks of today have successfully connected a vast majority of global population. After the birth of *Mobile Internet*, connecting billions of smart phones and laptop, the focus of mobile communications is moving towards providing ubiquitous connectivity for machines and devices, thereby creating the *Internet-of-Things* (IoT) [1]. The transition towards IoT is creating a new paradigm of 'control' communications.

In a natural evolution to different Internet embodiments, the notion of *Tactile Internet* [2] is emerging in which ultra-reliable, ultra-responsive, and intelligent network connectivity will enable the delivery of real-time control and physical haptic experiences remotely. The Tactile Internet will add a new dimension to human-machine interaction through building real-time interactive systems. The Tactile Internet will provide a true paradigm shift from content-delivery to skill-set delivery networks, and thereby revolutionize almost every segment of the society. Recently, standardization activities for the Tactile Internet have started to emerge within IEEE and ETSI [3].

Because the Tactile Internet will be servicing really critical aspects of society, it will need to be ultra-reliable, with a second of outage per year, support very low latencies, and have sufficient capacity to allow large numbers of devices to communicate with each other simultaneously and autonomously. It will be able to interconnect with the traditional wired Internet, the mobile Internet and the IoT – thereby forming an Internet of entirely new dimensions and capabilities. State-of-the-art fourth generation (4G) mobile communications systems do not largely fulfil the technical requirements for the Tactile Internet. Therefore, fifth generation (5G) mobile communications systems are expected to underpin the Tactile Internet at the wireless edge. An early assessment of 5G scenarios and requirements has been developed in the METIS research project [4], [5], and recently also by the telecommunications industry alliance NGMN [6]. With Tactile Internet, daunting new requirements and challenges arise for 5G network design.

Given these unprecedented mobile technology capabilities, we believe that 5G will play an integral part of the Tactile Internet connectivity ecosystem. Since research on Tactile Internet and 5G is at a nascent stage, the intersection of the Tactile Internet and 5G is the main focus of this paper. We begin our discussion by outlining some of most important Tactile Internet applications and use cases in Section II. After this, in Section III, we identify the Tactile Internet requirements which stem directly from the application scenarios and which resonate with many of the 5G requirements. In Section IV, we cover the architectural aspects of Tactile Internet and discuss various components of end-to-end Tactile Internet architecture. Finally, in Section V, conclusions are drawn and future work directions are highlighted.

II. Key Tactile Internet Applications

The Tactile Internet will enhance the way of communication and lead to more realistic social interaction in various environments. Current wireless local area network (WLAN) and cellular systems do not yield anything close to achieving an end-to-end latency of 1 ms which is crucial for Tactile Internet applications as shown in Section III-A. Therefore, it is difficult to comprehend a complete list of possible emerging Tactile Internet applications. In this section, some main examples are provided to show the ground-breaking potential of the Tactile Internet.

A. Self-Driving Vehicles

Technological advancements are creating a continuum among conventional, fully human-driven vehicles and autonomous vehicles, which partially or fully drive themselves. Autonomous vehicle technology with self-driving features will revolutionize the driving experience, and consumers will need time to learn how to use and manage the new features. In particular, self-driving vehicles are set-up with certain features such as self-parking, emergency braking, and adaptive cruise

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control and are already reality in selected applications that feature controlled environments.

A fully self-driving car, on the other hand, is also no longer a futuristic idea. Various companies have already released self-driving features that give the car the ability to drive itself. Compared to partially self-driving cars, fully self-driving cars' steering wheel will no longer exist.

Besides self-evident benefits, such as easier parking, significantly reduced (zero in the optimal case) accident rates, one of the key profits of self-driving cars is time saving. Autonomous car drivers will be able to spend traveling time working, relaxing, or accessing entertainment/digital media on the road which will have a big economic impact. However, these benefits come at the cost of supplementary challenges requiring significant improvement in 1) communication technologies, 2) hardware for the sensor domain in order to get a reliable environment model, and 3) the connectivity domain to obtain information from other cars and the infrastructure [7]. In order to facilitate fully self-driving capabilities, recent advancement in 5G wireless communication technologies and automobiles have enabled the evolution of Intelligent Transport System (ITS) [8] to wirelessly connected and communicating vehicles. Hereby, wireless communication technologies play a vital role in supporting both Vehicle to Vehicle (V2V) and Vehicle to Infrastructure (V2I) communication.

Enabling real-time communication and enhanced security, considerable and sustainable reduction of road accidents and traffic jams can be achieved by fully autonomous driving. The time needed for collision avoidance in today's applications for vehicle safety is below 10 ms [9]. In case of a bidirectional data exchange for automatic driving maneuvers, a latency in the order of a millisecond will likely be needed [10]. This can technically be realized by the Tactile Internet and its 1 ms end-to-end latency. Fully autonomous driving is expected to change the traffic behavior entirely. Especially small distances between automated vehicles, in particular in platoons, potentially safety critical situations need to be detected earlier than with human drivers. This requires ultra-high reliable and proactive/predictive behavior in future wireless communication systems.

B. Industrial Automation

All around the world, traditional manufacturing industry is on its way to be revolutionized by a digital transformation that is accelerated by exponentially growing technologies, e.g. intelligent robots, sensors etc.

Industrial countries have already witnessed three industrial revolutions, which could also be described as disruptive leaps in industrial processes resulting in significantly higher productivity [11]. In the first industrial revolution (starting in the 1780s), mechanical production facilities with the help of water and steam power was introduced. The second industrial revolution started in the 1870s and enabled the introduction of division of labor and mass production with the help of electrical energy. The use of electronic and IT systems further automated the production in the third industrial revolution together with the first programmable logic controller in 1969. The upcoming fourth industrial revolution (industry 4.0) is based on real-time enabled cyber-physical systems and comes with key changes in manufacturing, engineering, material usage and supply chain and life cycle management, i.e. leading to flexible and self-organized smart factories [12]. With increased agility and flexibility in the production process, industry 4.0 will enable to individualize any product and allow to react faster on changing market requirements. Cyber-physical systems in industry 4.0 comprise smart machines, storage systems, and productions facilities capable of autonomously exchanging (wirelessly) information, triggering actions, and controlling each other independently [13].

Industry 4.0 will naturally come together with some challenges. The services and applications provided by cyber-physical system platforms will connect people, objects, and systems to each other. This possesses novel requirements on safety, security, and reliability for everything from sensors to user interfaces in real-time [14], [15]. Among other issues, this will involve addressing the challenges posed by the wide range of different data sources and devices. Identified critical system parameters in smart factories are latency (+ jitter), safety, and energy consumption. Latency requirements of machines are in the range of several milliseconds, the sensitivity of rapidly moving devices' control circuits is significantly below 1 ms per sensor, while subsystems rely on a latency of several micro seconds [15]. Hence, smart factories together with automation in industry is a key application field in the Tactile Internet.

C. Tele-Medicine

Information Technology (IT) is a key in the field of e-health. Most of the technological advancement in wireless networking has been applied to advance healthcare services. E-health and health care services are information based and, hence, a better utilization of information can make health services more incorporated to enhance the patient safety. Consequently, wireless standards and IT need to be further improved to provide efficient, reliable, and robust real-time health services in tele-diagnosis, tele-surgery and tele-rehabilitation (i.e. tele-medicine). In [16], the impact of latency on a sergeant's precision in a robotic-assisted remote telepresence surgery has been examined. It has been shown that a non-real-time system leads to errors in the sergeant's behavior.

Tele-medicine uses (wireless) communication and information technology to overcome geographic distances, and increase access to health care services. Using advanced tele-diagnostic tools, medical expertise could be available anywhere and anytime regardless of the physician's location. Hereby, a tele-robot at the patient's location will be controlled by the physician, so that not only audio and/or visual information, but also haptic feedback is provided. The same technical principle is applied to tele-surgery applications.

E-health comes together with stringent requirements on the reliability of wireless connection. Especially in tele-surgery and tele-diagnostic, reliability is of particular importance. Unreliable connectivity can lead to delayed imaging, so that poor image resolution may limit the efficacy of the sergeant's remote handling. In addition, an accurate tele-medical treatment can only be realized with haptic feedback which in turn is possible if the (physician/) human-to-machine interaction can be facilitated in real-time. This requires a deterministic real-time behavior which is not supported by recent communication systems. An end-to-end latency of a few milliseconds together with ultra-high reliability in wireless link connection and data transmission is required in e-health which can be realized by the Tactile Internet.

D. Virtual and Augmented Reality

Existing virtual and augmented reality applications can significantly benefit from the availability of the Tactile Internet. The virtual reality is a shared, haptic virtual environment in which several users are physically coupled via a simulation tool to jointly/collaboratively perform tasks by perceiving the objects not only audio-visually but also via the touch sense. In augmented reality, on the other hand, the combination of real and computer generated content is visualized in the user's field of view. The major goal of future augmented reality applications, compared to today's static information augmentation, is the visualization of dynamic content and up-to-date information.

Haptic feedback in virtual reality is a prerequisite for high-fidelity interaction. Especially, the perception of objects in virtual reality via the sense of touch leads to various applications relying on high level of precision. This precision can only be realized if the latency between the users and the virtual reality is a few milliseconds.

The augmentation of additional information into a user's field of view enables the development of many assistance systems, e.g. maintenance, driver-assistance systems, education. With the Tactile Internet the content in augmented reality can be moved from static to dynamic. This enables a real-time virtual extension of a user's field of view, so that possible dangerous events can be identified and avoided.

E. Further Tactile Internet Applications

Additional Tactile Internet applications are serious gaming, education, individualized manufacturing, and unmanned autonomous systems. Serious games are real-world simulations designed for the purpose of solving a problem. The end-to-end delay in the interaction between players and games is a key factor influencing the quality of players' experience and the game's usability, since the delay influences directly the perceived realism of the game.

Individualized manufacturing unlike the mass production in today's assembly line based production processes will enable the manufacturing of good in production islands. Hereby, mobile robots will deliver assembly parts on demand. This requires a wireless real-time tactile communication network among the mobile robots.

Unmanned autonomous or remotely controlled systems are increasingly used in a large number of contexts to support humans in dangerous and difficult-to-reach environments, remotely controlled by humans, or for tasks that are too tedious or repetitive for humans. The remote control of an unmanned aircraft, for example, can be realized with high precision and without any reaction delay with a reduced end-to-end latency as a Tactile Internet application.

III. Technical Requirements

The Tactile Internet, wherein humans will wirelessly control real and virtual objects, will not be realized without overcoming the enormous system design challenges. Some of the most stringent design challenges for the Tactile Internet have been recently presented in [17].

In the following, we highlight the key technical requirements for realizing the Tactile Internet.

A. Ultra-Responsive Connectivity

The Tactile Internet requires ultra-responsive network connectivity i.e., end-to-end latency on the order of 1 ms [18], [19]. For real-time transmission as otherwise the tactile users will experience cyber-sickness, which occurs primarily as a result of conflicts between visual, vestibular, and proprioceptive sensory systems [20]. Thus, if eyes perceive a movement which is slightly delayed compared to what is perceived by the vestibular system while the remainder of the human being's body remains static, this delay leads to cyber-sickness. This is especially important for technical systems with tactile and haptic interaction or for mission critical communications, e.g. machine-type communication which enable real-time control and automation of dynamic processes in industrial automation, manufacturing, traffic management, etc.

The end-to-end latency (round-trip delay) in technical systems includes the time spent in the transmission of the information from a sensor (or human in case of haptic interaction) via the communication infrastructure to a control server; the processing of the information and the eventual retransmission via the communication infrastructure back to the actuator (human). Considering an end-to-end latency of 1 ms the latency budget for wireless transmission is even lower than 1 ms (see Fig. 3).

B. Ultra-Reliable Connectivity

The phenomenal success of cellular networks has been based on providing ubiquitous and reliable wide area coverage for voice and text communications. With 4G and the success of mobile computing devices the industry is targeting to bring the same reliability and ubiquity of access to mobile internet applications such as web browsing and audio and video streaming. The Long Term Evolution (LTE) today already is providing effective data rates of around 50 Mb/s. However, considering technology and market forces in 10 years, we must be able to address cellular speeds of 10 Gb/s or more and introduce new applications [4], [21], [22]. While high data rates will be a key feature of 5G networks, another key challenge is to be able to provide carrier grade access reliability. Beyond single digit end-to-end latency, ultra-reliable network connectivity is an important requirement for the Tactile Internet. Reliability refers here to the probability to guarantee a required function/performance under stated conditions for a given time interval [23]. The specific reliability requirements differ for various types of services and applications.

Demands for the highest possible reliability are associated with requirements for real-time response. This becomes clear, with applications addressed in Section II requiring a reliable reception of rapidly transmitted data. A failure rate even below 10^{-7} might be necessary in some 5G applications [24], [25]. This corresponds to merely 3.17 seconds of outage per year. Wireless systems of today are built around the perception that a link with 3% outage is a good link. However, when two links with uncorrelated channels are combined, 3% outage per link generates a combined outage of approximately 10^{-3}. And five uncorrelated links can already achieve an outage of less than 10^{-7} [26]!

Hence, the simultaneous connection to multiple links (multi-connectivity) might be a potential solution for achieving the required hard-bound (i.e. not average!) reliability for tactile applications [27]. The achieved reliability will also have a positive impact onto delay since less re-transmissions will be needed.

C. Security and Privacy

Safety and Privacy are also the key requirements for the Tactile Internet. With stringent latency constraints, security must be embedded in the physical transmission and ideally be of low computational overhead. Novel coding techniques need to be developed for tactile applications that allow only the legitimate receivers to process a secure message. Absolute security will, hereby, be achieved if an illegitimate receiver cannot decode the date even with infinite computational power. This rises a challenge, especially in massive connectivity applications. Identification of legitimate receivers requires novel reliable and low-delay methods. One such method could be the usage of hardware specific attributes such as biometric fingerprints.

D. Standard Codecs Family

The Tactile Internet must handle the tactile information in the same way as the conventional audio/visual information. Hence, a standard codecs family, similar to the state-of-the-art audio (ITU-T H.264) and video (ISO/IEC MPEG-4) codecs is needed, which facilitate transmission of tactile data over packet-switched networks. Such a codec family would be a key enabler for scalability at the network edge and universal uptake. Besides, there must be provisioning of audio/visual sensory feedback due to the highly multi-dimensional nature of human haptic perception [28].

E. Edge Intelligence

The Tactile Internet must overcome the fundamental limitation due to finite speed of light. Without this, the range of tactile services and applications would be limited to 100km (assuming most is through fiber). To overcome this, the Tactile Internet must support a hybrid composition of machine and human actuation mixing real tactile actuation with intelligence-based predictive actuation. Such predictive actuation should be in close proximity of the tactile edge. Therefore, the edge of the network (mobile edge cloud) must be equipped with intelligence to facilitate predictive caching as well as interpolation/extrapolation of human actions. This necessitates the development of novel artificial intelligence techniques for edge cloud architectures.

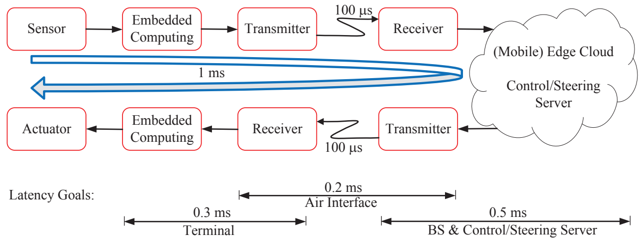

Fig. 1. Examplary latency objectives of Tactile Internet systems.

IV. Architectural Aspects

Unlike the conventional Internet which provides the medium for audio and visual transport, the Tactile Internet will provide the medium for transporting touch and actuation in real-time i.e., ability of haptic and non-haptic control through the Internet. Unlike auditory and visual senses, 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 [29]. The key distinction between haptic and non-haptic control is that in case of the former, there is actually a haptic feedback (*kinesthetic* or *vibro-tactile*) from the system, in addition to audio/visual feedback, thereby closing a global control loop; whereas in case of the latter, the feedback can only be audio/visual and, hence, there is no notion of a control loop. It should be noted that the haptic control is inherent to a majority of tactile applications.

As shown in Fig. 2, the end-to-end architecture for the Tactile Internet can be split into three distinct domains: a master domain, a network domain, and a slave domain.

A. Master Domain

The master domain usually consists of a human (operator) and a human system interface (HSI). The HSI is actually a haptic device (master robot), which converts the human input to tactile input through various tactile coding techniques. The haptic device allows a user to touch, feel, and manipulate objects in real and virtual environments, and primarily controls the operation of the controlled domain as discussed later. The master domain also has the provisioning for auditory and visual feedbacks. In addition to being important requirement for non-haptic control, the auditory and visual feedbacks play a critical role in increasing the perceptual performance as the human brain naturally integrates different sensory modalities [30].

State-of-the-art haptic devices, available from vendors like Geomagic and Sensable are usually designed in the form of a linkage-based system which consists of a robotic arm attached to a stylus. The robotic arm tracks the position of the stylus and is capable of exerting a force on its tip. To truly realize the vision of the Tactile Internet, further developments on haptic devices are needed; particularly in increasing the degrees of freedom (DoF) to meet the demands of envisioned applications and embedding the wireless interface for direct or indirect communication with the cellular network.

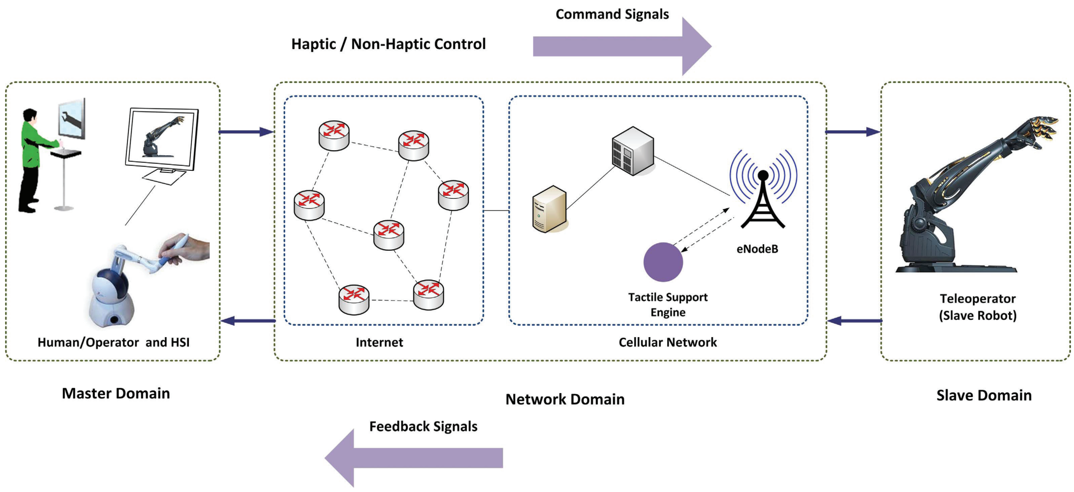

Fig. 2. Functional representation of the Tactile Internet architecture.

B. Slave Domain

The slave domain consists of a teleoperator (controlled robot) and is directly controlled by the master domain through various command signals. The teleoperator interacts with various objects in the remote environment. Typically, no *a priori* knowledge exists about the environment. Through command and feedback signals, energy is exchanged between the master and controlled domains thereby closing a global control loop.

C. Network Domain

The network domain provides the medium for communication between the master and controlled domains, and therefore couples the human to the remote environment. Ideally, the operator is completely immersed into the remote environment. The Tactile Internet requires ultra-reliable and ultra-responsive network connectivity that would enable typical reliabilities and latencies for real-time haptic and non-haptic interaction. The underlying 5G-driven communication architecture, composed of the radio access network (RAN) and core network, is expected to meet the key requirements in realizing the vision of the Tactile Internet.

To this end, the important functions of 5G RAN in the Tactile Internet ecosystem are as follows:

- Efficient support of various radio access technologies (RATs) such as traditional cellular, emerging millimeter-wave, massive MIMO, full-duplex, etc.
- Tactile QoE/QoS aware scheduling and radio resource management for tactile applications in co-existence of other vertical applications such as machine-to-machine, vehicle-to-vehicle, smart grids, etc.
- Efficient packet delivery through reliable radio protocols and physical (PHY) layer.
- Optimal resolution of air-interface conflicts through novel medium access control (MAC) techniques.

The legacy LTE networks will be an integral component of the 5G ecosystem. The overall 5G wireless access solution will comprise of *evolved* LTE air-interface (with backwards-compatible enhancements) co-existing with new air-interface (e.g., NX) in new spectrum.

The key functionalities of the 5G core network relevant to the Tactile Internet are as follows:

- Dynamic application-aware QoS provisioning
- Cloud-based edge intelligence
- Security

Overall, a *thin* core network with substantial decrease in the protocol overhead is desirable. The thinning of the core network can be achieved by its functional decomposition and moving some of core functionalities to the access network. This will reduce the number of nodes in the data path and hence reduce the end-to-end latency

Although a number of research efforts are focusing on 5G systems, there is no unanimous agreement on a 5G network architecture yet. However, both the academic and industrial communities have a general consensus that 5G networks must be designed in a flexible manner such that one network, based on a common physical infrastructure, is efficiently shared among different vertical applications. Such sharing will be possible through greater degree of abstraction of 5G networks wherein different network slices would be allocated to different vertical application sectors. A network slice is defined as a connectivity service based on various customizable software-defined functions that govern geographical coverage area, availability, robustness, capacity, and security [31]. Such slicing approach provides more of a *network on-demand* functionality.

The recent trends of network function virtualization (NFV) (providing abstraction [32]) and software defined networking (SDN) (providing flexibility [33]) are critical in shaping such an envisioned architecture. NFV provides the separation of network functions from the hardware infrastructure; the network function can be managed as a software module that can be deployed in any standard cloud computing infrastructure. On the other hand, SDN provides an architectural framework wherein control and data planes are decoupled, and enables direct programmability of network control through software-based controllers [34].

Whilst SDN/NFV was initially proposed for the Internet infrastructure, the approach is now being considered/used closer to the edge in the cellular CN and even Cloud-RAN. That opens the interesting possibility to provide an end-to-end flexible/abstracted architecture based on radio-aware SDN/NFV slicing in the networking domain and network-aware Radio Resource Management (RRM) & scheduler approaches in the wireless domain. Through such a coupling, it is possible to design one network in a flexible manner offering different end-to-end network slices to different vertical applications. Such an architectural approach enables flexible and dynamic slicing of end-to-end network and service resources, which is particularly attractive to cater for the requirements of tactile as well as other vertical applications.

V. Concluding Remarks

It was the aim of this article to investigate the interesting area of 5G and Tactile Internet intersection. After discussing the exciting Tactile Internet applications, key technical requirements and architectural aspects for the Tactile Internet have been discussed. Realizing the Tactile Internet will not be possible without overcoming enormous set of design challenges. Pertaining to 5G network design, novel Physical layer transmission techniques, advanced wireless access and core networking protocols, and unprecedented edge intelligence capabilities come at the forefront of research challenges. The biggest challenge – given the unprecedented requirements on delay and reliability – will be to ensure tight whilst at the same time scalable integration of the various technology components into a single, seamless end-to-end networking experience. Once achieved, the Tactile Internet will have a massive impact onto business and society. It will create new opportunities for vendors, operators, content providers and other members of the service chain.

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