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Architecture for Scalable, Self-*, human-centric, Intelligent, Secure, and Tactile next generation IoT

ASSIST-IoT Technical Report #3

Tactile Internet in Internet of Things Ecosystems

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Abstract. The aim of this contribution is twofold. First, to summarize the state-of-the-art in the area of Tactile Internet. Second, to outline, based on pilots of the ASSIST-IoT project, an architecture needed to realize Tactile Internet in Internet of Things ecosystems.

Keywords: Tactile Internet, distributed systems, 5G networks, Internet of Things, haptic interfaces

1 Introduction

Tactile Internet (TI) is one of recent pivotal technological trends. According to the International Telecommunication Union – Telecommunication Standardization Sector (ITU-T), Tactile Internet is defined by *"extremely low latency, in combination with high availability, reliability and security"* [1]. It refers to systems leveraging extra fast networks, enabling haptic human-machine interaction.

Applications of TI are multiple and diverse, and its relevance, observed in the literature, is growing fast (e.g., since the introduction of the term in 2014, in the first paper [2], more than 135 related articles have been published in 2020, and the trend continues to grow in 2021). All works support the claim that Tactile Internet reaches far beyond data streaming over fixed and/or mobile networks, and provides a new dimension to the Internet, by improving availability, reliability and latency. In addition, the upsurge of related technologies such as social robots, wireless sensing networks, and the Next Generation Internet of Things (NGIoT), contribute to the rise of the Tactile Internet. What follows summarizes key aspects of Tactile Internet of today (Q1, 2021) and outlines key aspects of the NGIoT architecture that can be seen as TI-ready.

2 Why is Tactile Internet Needed?

For Tactile Internet to be understood, let us outline why it came into being. The advent of TI emanates directly from needs expressed by the industry and the technological community. The following sections contextualise the need of TI.

2.1 Foundations of Tactile Internet

Internet communication infrastructure is used mainly to transfer information between "specific points". As Internet evolved, it was possible to improve the key parameters of data transmission, e.g. latency, or data rate. This brought new possibilities, such as remote operation of heavy machinery, or remote healthcare. As a result, a technological trend has emerged, focused on offering point-to-point communication with extreme low latency and high reliability. Not only does it bring about new communication paradigms (e.g. haptic data[3]), but also provides foundation for the next generation of applications (see also, Section 2.2).

Standardisation/research groups The ITU-T was one of the first research and standardization groups that mentioned Tactile Internet [1]. The IEEE SAB presented the IEEE 1918.1 as an IEEE Standards Working Group devoted to Tactile Internet [4]. This standard defines the concept, and includes definitions, terminology, and application scenarios. Moreover, it includes the reference model and the architecture, which define architectural entities, interfaces, and mappings. Finally, the European Telecommunications Standard Institute (ETSI) has created a group that considers impact of IPv6 across technologies, including Tactile Internet [5]. There have been other actions targeting TI, but using other names, such as the 5G–NR (New Radio; [6]), released by the 3GPP that aims at providing enhancements related to Ultra-Reliable Low Latency Communication.

Communities/Clusters In 2016, an Alliance for the Internet of Things Innovation (AIOTI) was initiated, to contribute to development of the European IoT ecosystem. It defined TI, in the *Standardisation Working Group*, as a technology enabler for ultra-high reliability, and ultra-low latency applications, where the network is part of a haptic feedback loop [7]. The NG-IoT Initiative [8] (part of the ICT-56 cluster [9]), introduced TI as one of the enabling technologies for the next generation IoT. Aiming at creating a competitive ecosystem of technologies for IoT, a series of projects seeks to include TI based on human-centric sensing, and new IoT services, e.g. integration of computing capabilities, neuromorphic computing, etc. Here, it is expected that TI will be enabled by, and grow with, IoT, AR/VR/MR and contextual computing.

Strategic technological trends Tactile Internet is focused on enabling real-time physical interaction, involving real and/or virtual objects. Technical requirements for the TI will need to be addressed by innovative technologies, which are fast maturing [10]. Among them, key is the deployment of 5G networks, to achieve Ultra Reliable Low Latency Communication, and enable human control of real and virtual objects, in real-time [11]. Furthermore, developments

[3] Usually, defined as any data created to provide haptic feedback, which allows users to touch, feel, and manipulate physical, or virtual, objects through remote machines. Here, the data rate is 1 KHz or higher [3]; see, also, Section 3.1

are accelerated by unexpected needs, such as the health emergency, caused by COVID-19. Here, use of remote communication has "exploded", pushing development of applications requiring TI. Moreover, studies of 2021 technology trends ([12]), emphasise such "interaction" as a key emerging trend at the macro level.

2.2 How the Industry expresses the necessity of Tactile Internet

Recently, the Industry has been facing problems that go beyond visual and/or hearing interactions, and require introduction of the Tactile Internet. One example is use of robots in manufacturing. Managing such machinery remotely, replicating movements of operators, without risking their health, has been reported, among others, in [13]. Moreover, critical applications, where humans are involved, may benefit from the TI. Here, consider remote surgery, which requires ultra reliable, low latency, robust systems [14]. The number of verticals in need of TI is huge. Consider, for instance, addressing the following needs:

- To facilitate the remote on-the-field intervention of experts, who would be put at risk if present at a given physical location. Here, availability of haptic movements, actionable through a machine (e.g., robot) is needed.
- To facilitate remote operations in inaccessible places (e.g., drones flying over fires, actions within deep seabed locations, rescue missions, etc.).
- To create remote experiences, allowing visiting sites without being physically present. Here, large scale deployment could imply enormous benefits in various contexts (e.g., reducing traffic, transfer of people, etc.).
- To boost teleworking. Some jobs require physical presence of operators, or other workers that must perform "manual/touchable" tasks. These actions could be replicated by robots, provided that TI becomes fully operational. This has being recognised as paramount in the context of COVID-19 pandemic, and the need for social distancing measures [15].

Furthermore, TI will generate new business opportunities, and academic/research lines. In particular, companies devoted to communication technologies are well positioned to play a major role exploring potential of Tactile Internet.

3 What does Tactile Internet entail?

Some works, like [16], have classified the Tactile Internet using an application taxonomy (wireless networked control systems, remote operation systems, immersive entertainment and edutainment systems, intelligent mobility systems, smart energy systems), or as a global field composed of enabling technologies (high-performance wireless, connectivity requirements, and vision). The authors of this work consider, drawing from the experience gained in the ASSIST-IoT project (see Section 5), that TI must be understood as any system that (i) successfully carries haptic data by (ii) relying on a communication meeting the requirements of (a) low latency, (b) high reliability, and (c) high data throughput. Following sub-sections aim at describing the meaning of each of these aspects.

3.1 Haptic data and haptic codecs

Tactile Internet's mission is to enable exchange of haptic data, facilitating novel human-machine interaction. Haptic information can be expressed through various parameters, e.g.: force, movement, vibration or texture. Usually, such data is generated by haptic feedback devices that can be divided into: cutaneous (involving skin features, e.g. pressure, touch intensity, temperature or pain) and kinesthetic (relying on relative position of neighbouring body parts, and capturing, e.g., muscle tension) [17]. Two scenarios can be further defined, depending on the communication: (i) closed-loop feedback (i.e. perception) that require being as-close-to-real-time-as-possible (delay intolerant) and (ii) open-loop feedback, which are less restrictive, and accept time-delayed communication.

The most relevant characteristic in haptic data transmission is information encoding (IEEE SAB group 1918.1.1). Similarly to audio signals (using e.g., MP3 or HVXC), or image frames (using e.g. PNG or JPEG), encoding schemes are needed for haptic feedback to allow final ends of communication to understand each other (speak the same language, set plug-and-play communication, etc.).

The algorithms taking care of encoding are called "codecs". Currently, the encoding proposals (based on haptic codecs, such as block-based processing, or frequency-domain models [18]), are combined with audiovisual transmission, to provide the feeling of being present in a remote environment, allowing to work in distant or inaccessible situations (see Section 2.2). In the most restrictive TI scenario (closed-loop, above), there is the need for the codecs (apart from enabling communication) to reduce amount of data transmitted (number of packets). To do so, current approaches rely on mathematical models of human perception.

Overall, encoding schemas – and associated codecs applying data transformation algorithms – are an open research line aimed at reducing the amount of transmitted haptic data, to reach validity of human perception.

3.2 Infrastructure requirements

While the technology stack, needed to support TI, is still under development, the necessary requirements can be assessed. Tactile Internet communication must be characterised by strict latency and Quality of Experience (QoE) restrictions. Due to human involvement, there is a limitation imposed by the sensation of touch, estimated at a time resolution of 1000 Hz [17]. To offer a realistic experience, TI must offer communication latency of 1 ms, from the moment the action starts (e.g. user moves a finger, or remote operator presses the edge of a glove), till the feedback is received. Assuming that communication paths cannot reach the speed of light, the maximum distance between TI endpoints is limited to 150km [1].

However, TI also requires communication infrastructure delivering both high availability and high reliability. Based on [19], let us summarize the infrastructure requirements (see also Figure 1):

- **Low-latency.** In a generic case, the time-consuming operations are: running user interface, data transmission, and computing. For TI to deliver seamless, low-latency, connectivity, it should take full advantage of 5G networks,

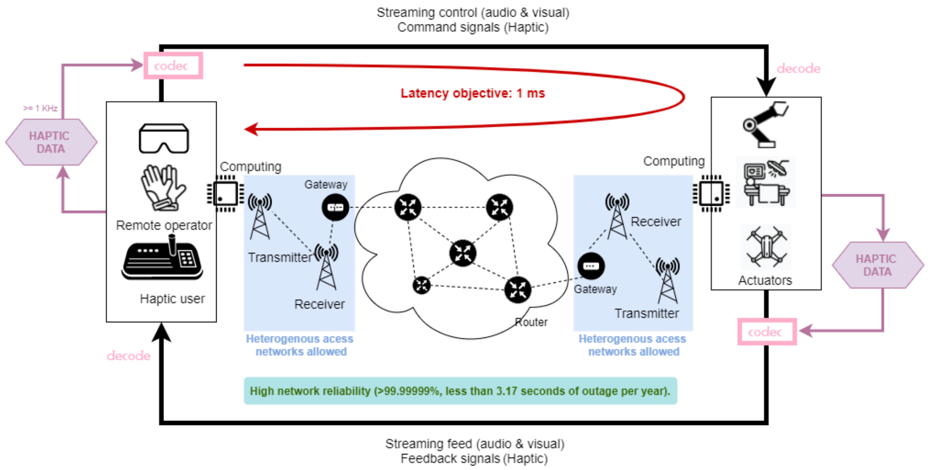

Fig. 1. Visual summary of the infrastructure requirements of the Tactile Internet. Copyright note: Flaticon

delivering round-trip latency in the millisecond range. However, 5G may not be available. Hence, robust implementation should be possible also over WLAN, sub-GHz technology, and their combinations [20]. This is why technologies, like Software-Defined Networking (SDN) and Virtualised Network Functions (VNFs), are explored to significantly reduce latency, by optimising data transmission [21]. When fast-enough communication cannot be guaranteed, other techniques may be used. Here, in [17], use of Artificial Intelligence is suggested (based on regression models and linear predictions) leveraging previously received values. However, such complex approaches may be useful if the computation is realized "close to the user". Therefore, they should be placed at the edge of the network (e.g., Mobile Edge Computing; MEC [22]).

– **High reliability.** In all communications, the goal is to make them speed-optimal and error-less. However, this can be very difficult, due to environmental conditions, or strict requirements of the application. This involves, for instance, need for extremely high level of reliability, due to the consequences that can arise from communication errors. Consider a target of 99.99999% availability (of a remote surgery system), allowing outages of only 3.17 seconds per year. Separately, to ensure the integrity of data, security mechanisms are needed. Obviously, security is important also when haptic data is processed on a remote server, as data travels between the device and the MEC server. Here, encryption techniques are needed. However, they imply additional delay in communication [17], so a trade-off must be found.
– **High data throughput.** Haptic-enabled VR/AR/MR applications require high data throughput. However, transmission is the most critical point for moving large volume of data in (near) real time, becoming one of the most demanding limitations of TI. This is because of the amount of data that

moves, the needed bandwidth, and lack of buffer that manages the reception. A promising solution would be to increase the transmission frequency. However, use of narrow beamwidth directional antennas, required to reduce the high path loss at mmWave, may result in frequent link outages, due to antenna misalignment. To support TI applications, a hybrid radio access architecture was proposed [23]. Here, sub-6 GHz access is used for transmission of haptic information, while mmWave access is used for high data-rate transmission of audiovisual information.

Overall, Tactile Internet has strict technological requirements for end-to-end communication, data encoding, and overall network availability, to achieve actual real time interaction. As noted, several open challenges are currently faced, while alternative technologies (e.g. SDN, NFV, narrow beamwidth antennas, MEC at 4G/5G) have been proposed to meet strict communication requirements. However, the state of the art does not currently point to a clear reference product/solution that gathers all previous innovations in a single specification.

4 Reference initiatives

Lately, some efforts have started to formalise a reference Tactile Internet specification, with tentative applications in real-world scenarios. However, up to this point, there is not a clear standard to stick to in terms of TI deployment. This section briefly outlines the most relevant initiatives with that purpose.

4.1 Theoretical and application agnostic solutions

Since being proposed, Tactile Internet has been associated mainly with a communication structure, focused on the interaction between the end-points (transmitter-receiver, client-server, publisher-subscriber, user-remote machine). In 2014, the ITU-T [1] proposed to frame communication within TI systems using a master-slave schema, reasoning that it is most natural, and drawing from the legacy, pre-TCP/IP era telecommunication systems. Here, the **master** as the "commander", issues actuation orders to the **slave**, which is in charge of "performing" the command. In the context of Tactile Internet communication, the master would be, for instance, a remote controller entity (human or machine) that, through an interface, codes haptic input into command signals and sends them to the slave. The slave could be an object/robot, directly guided by the remote controller (master), capable of providing feedback and closing the loop [24].

The architecture proposed by the IEEE 1918.1 follows the same master-slave concept, but improves the edge connectivity, by setting a gateway node to connect slaves to the network. The architecture included the gateway node at the edge, near to the master and slave actuators, or in the domain network.

Contributions from ITU-T and IEEE, along with other architectures found in literature, are mainly theoretical and generic, and do not include real/practical aspects (e.g., including a list of technologies and how to "glue them together") to implement TI. Moreover, they lack a link to the role that IoT (sensors, gateways, actuators, data exchange, access networks) are to play in specifications.

Separately, multiple projects introduce alternative vision of Tactile Internet. In FlexNGIA [25], a TI infrastructure is based on network applications. Leveraging computing capacities of network elements, FlexNGIA proposes to deploy services as network functions. FlexNGIA defines a business model where network operators could offer not only data delivery but also service chains, with stringent requirements in terms of performance, reliability and availability.

Other projects, like TACTILENet [26], implement TI in a network architecture that adapts to the QoE requirements of specific scenarios, instead of uniformly delivering higher capacity and higher reliability. TACTILENet has roots in cloud densification (spatial overload and spectral aggregation), green energy efficiency, and Cross-layer Machine-type Communications.

Next, TACNET 4.0 [27] is focused on 5G integration, through an architecture designed to support remote control of mobile machines/robots, allowing workers to interact through AR devices. TI is achieved using 5G, and a management and control plane that ensures efficient use of resources, to improve reliability.

Other proposals offer integration of specific novel technologies to support vertical application requirements. For instance [20] enables flexible and dynamic slicing, by integrating SDN and NFV with fog computing, and creating a hierarchy where the SDN controller manages the network. To improve latency and reliability, by reducing network congestion, a multi-level cloud system, described in [22], provides offloading through MEC. Improvements in network capacity can be based on enhancing LTE-A heterogeneous networks fiber backhaul and WiFi offloading capabilities [28], while in [29] this is achieved by simultaneously transmitting over multiple wavelength channels in Ethernet Passive Optical Networks.

4.2 Specific solutions

As noted, early realizations of TI can be found in the literature. Here, we briefly overview key publications, dividing them into "application domains". It should be noted that the described approaches implicitly express urgent need of a valid, robust, scalable reference architecture, focused on practical implementation of the Tactile Internet. Provided examples illustrate variance of significance of TI requirements, from one application to another.

- **Mechatronics**: human-humanoid robots interaction, combines electronics, computing, telecommunications, etc., to create robotic systems. These systems can be managed in real-time by a human-machine communication following the master-slave concept. In mechatronics [13], the human interacts with a remote body to execute various skills, physically linking the virtual and the real worlds. Here, applications face strong real-time requirements, as in remote surgery [30], where an increase of latency, or packet transmission errors, can lead to serious consequences. An example of this vertical can be found in [31], proposing a remote controlled exoskeleton, which is not that demanding on reliability, but requires a reaction time fast enough to feel real-time movements. Some approaches set multi-robot applications, allocating physical and/or digital human tasks to robots. In [32], an integrated Fiber-Wireless multirobot network architecture is proposed, coordinating local and non-local Human-to-Robot task allocation. Other projects, as Ocean One [33] design an architecture that allows human-robot interaction, not only with video and haptic data, but also with GPS coordinates. Reliability requirements materialize in industrial applications (e.g, safety control or health interventions) where 99.9999% is acceptable, but 99.99999% is desirable.

- **Virtual Reality (VR)**: video transmission applications do not involve haptic data, either because the master only needs image and sound to control the system, or because a machine-to-machine communication is carried out, and video data is absent. However, high resolution images, and 3-D stereo audio, in VR and AR applications demand massive flow of information, and bring different challenges. For instance, network throughput, or delay performance, has to become less than 10 ms latency, to avoid cybersickness [17]. Some use scenarios, e.g. a free-viewpoint video, allows digital image processing to synthetically render the viewpoint of the viewer to another spot.
- **Helmet-mounted applications**: a remote VR phobia treatment architecture is proposed in [34], using MEC networks to reduce computation delay, and mmWave communications to increase network capacity. Note that, thanks to similar innovations, new helmet-mounted VR devices have emerged, e.g. Oculus VR, HTC Vive, or Microsoft Hololens.
- **Ultra-realistic videogames**: VR games may use TI to perform real-time interaction. System, described in [35], proposes mmWave Access Points, to reduce latency, and edge computing to minimise communication errors.
- **Unmanned aerial vehicles (UAV)**: video surveillance application [36], use UAV with cameras, interacting with sensors and actuators, installed on the ground. Due to the long time required on the transmission of video, from the drone to the cloudlet, or MEC ground-servers, a microcontroller is installed on board of the drone, to process incoming data, make decisions, and send activation messages to ground-based-actuators. Here, TI applications that do not require human presence, use data transmission optimisation; e.g., in autonomous driving, vehicles make decisions during driving events. This application requires low-latency and high-reliability, with extremely high-availability, due to potentially tragic consequences of accidents.
- **Vehicle-to-Vehicle (V2V)** applications: in [37], a scenario, for broadcasting messages only, covers communication patterns, where either a vehicle, or a pedestrian, can send the information of its location or velocity, so the receiver can calculate the relative position to avoid collision, or to facilitate operation in emergency situations. In [38], a testbed, based on flexible and re-configurable software-defined radio, is proposed, to improve cooperative automated driving. The system includes a re-configurable frame structure with fast-feedback, a novel P-OFDM waveform, low-latency multiple-access scheme, and a robust hybrid synchronization.
- **Smart Cities** applications: also use TI and relevant M2M communications. In [39], a quality of experience (QoE)-driven five-layer Tactile Internet archi-

tecture is proposed. It includes inter-band spectrum aggregation in transmission, and osmotic computing to handle offloading in cloud edge integration. Network optimisation, adapting resources to the demands, is achieved by intelligent decision-making in the application layer.

5 ASSIST-IoT approach towards Tactile Internet

Let us now introduce ASSIST-IoT[4], a H2020-funded project that aims at design of a decentralised NGIoT architecture to support human-centric applications. The solution will integrate 5G, AI-based functions, Edge/Fog computing and SDN/NFV (among other technologies), considering Tactile Internet as one of key objectives. In this context let us note that, as discussed, TI has been positioned mainly as a way to solve problems within vertical application areas. However, it was also shown that infrastructure requirements play a major role in TI systems, and those requirements might vary between application domains. Henceforth, it is crucial to include TI's strict limitations in the architectural decisions of any forthcoming IoT/distributed systems reference architecture(s).

In this context let us note that although the architecture designed in ASSIST-IoT will be application-agnostic, it will be bottom-up validated. Specifically, the ASSIST-IoT project is grounded in three application areas (industries): maritime port terminals, construction and automotive. Within these industries, four pilots have been formulated. The scope of these pilots, as related to Tactile Internet, has been summarized in Table 1.

Material presented thus far, supported by the content of Table 1 allows us to outline the key aspects of the ASSIST-IoT architecture that have been conceived to support Tactile Internet. Note that this is a preliminary vision of the architecture, and only the TI-focused aspects are reported. Overall, ASSIST-IoT approach to the next generation of IoT architectures is based on three premises:

- The architecture has to be **domain-agnostic** and the implementation has to support all kinds of applications.
- Architecture has to be **flexible** and adapt to different situations, depending on the requirements (note that all scenarios require high capacity network). Recall that applications may require (a) high-availability (such as autonomous driving), (b) bandwidth (such as video surveillance monitoring in drones, or (c) latency (such as remote mechatronics). In this context, ASSIST-IoT goes beyond the current landscape in two areas: (i) proposing and intelligent management of the available network resources to avoid interruptions in communication, or congestion in any node of the network, and (ii) allowing dynamic (automation to be explored) modification of the network, for changing scenarios and requirements within the same deployment, leveraging SDN and NFV techniques.
- To achieve this, ASSIST-IoT proposed a novel meaning to the term "enabler", which can be understood as a grouping of containerized components,

[4] `https://assist-iot.eu/`

Table 1. Tactile Internet in ASSIST-IoT

Pilots	**Actors**	**Equipment**	**Requirements**
Pilot 1 – Port automation	Remote operator	Container Handling Equipment (CHE)	**Latency** Remote control with end-to-end latencies below 50 ms **Reliability** Remote Operating System expected to work 99% of the time **Others** Enough communication bandwidth to ensure video streaming (around 30 Mbps)
Pilot 2 – Smart safety of workers	Construction worker	Fall arrest equipment	**Reliability** Precise construction worker localisation service is expected to work 99,99%
Pilot 2 – Smart safety of workers	Construction worker	Dangerous zone alarm	**Latency** Alarm construction worker about entering dangerous area (e.g. construction plants) **Reliability** Precise geo-positioning of construction worker vs. construction plants
Pilot 2 – Smart safety of workers	Construction worker	Evacuation instructions	**Reliability** Precise geo-positioning of construction worker **Others** Enough communication bandwidth to ensure that in case of jeopardizing events all construction workers will receive their evacuation plans and will be navigated. Evacuation plans will be regularly updated
Pilot 3 – Cohesive vehicle monitoring and diagnostics	Driver	AR interfaces	**Others** Enough communication bandwidth to ensure video streaming of the vehicle, on a mobile device (around 30 Mbps)

that together deliver a specific (micro)service and act towards a single goal (to provide a specific functionality) framed within a specific plane of the architecture (see Figure 2), providing deep **modularity**.

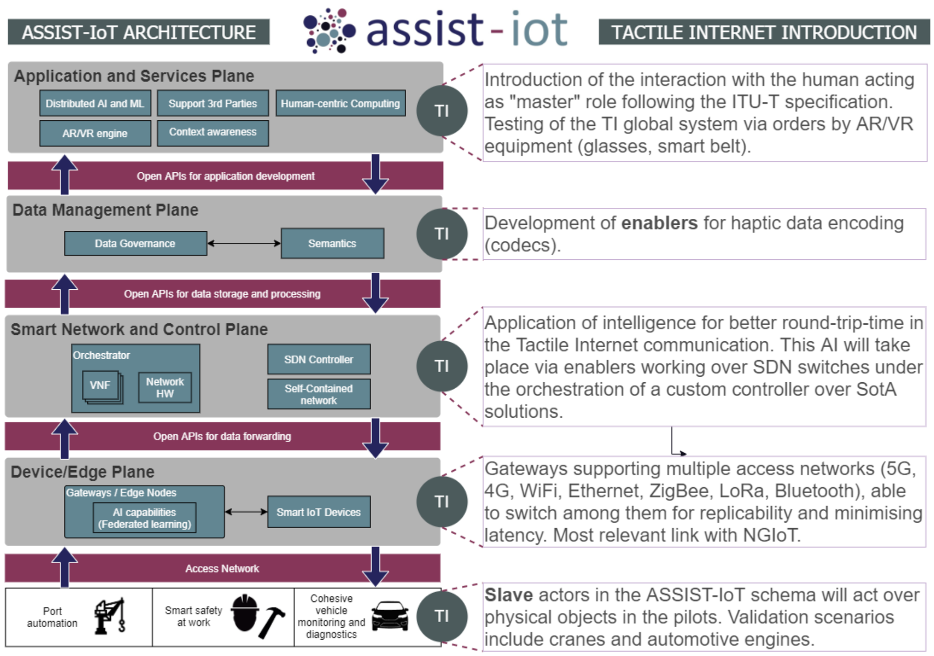

Fig. 2. ASSIST-IoT approach towards Tactile Internet.

Taking into account information available within Figure 2, we can summarize the way that ASSIST-IoT proposes to introduce TI, in its NGIoT architecture.

- Introduction of the interaction with the human in the Application and Services plane. AR components will provide new ways of accessing and configuring IoT environments for operation and training, supported by edge computing nodes and smart network capabilities, to achieve a low latency environment, and using advanced visual information systems to make better informed decisions by people/workers. Here, the human interface will act as a **master** role, existing in the three pilots to be deployed in the project.
- At the Data Management plane, **enablers** for haptic data encoding mechanisms (softwarised codecs) will be provided. Additional enablers, for aggregating and semantically annotating haptic data, needed to encode the information are envisioned.
- In the Smart and Network Control plane, virtualised low-latency networks (with embedded DLT for security) will provide tactile support for real-time

application. This will be achieved leveraging SDN-enabled switches through customised controllers.

- Regarding the Device and Edge plane, the IoT gateway will support multiple access networks (5G, 4G, WiFi, Ethernet, Zigbee, LoRa, Bluetooth) and will be able switching between them for redundancy, and to minimise latency.
- Finally, haptic actuators and sensing networks will support human-centric approach to development of TI-oriented services and applications, thanks to use of decentralised edge approach to deliver low-latency for haptic interfaces.

6 Concluding remarks

The presented work has reviewed the current state of Tactile Internet as a concept, digging also into its technological nature, and outlining how it has emerged both as an industry need and as the next step needed for evolution of Internet of Things ecosystems. In addition, the actual meaning of the Tactile Internet, in term of infrastructure requirements and the type of data that manages was considered. It was suggested that, while the requirements and constraints may vary from one application to the other, there exists the common quest of reducing round-trip latency, in a highly reliable system, looking for providing real feeling of participatory perception to the user. Besides, it has been argued that TI's wide scope has opened a myriad of different deployment approaches (promoted – or not – by standardisation entities), preventing the state-of-the-art to come up with a clear implementation reference (architecture) to build on. Finally, it has been suggested why ASSIST-IoT may deliver such a reference, drawing from a novel, dynamic, intelligent architecture that will be validated in four pilots, each with Tactile Internet ambitions.

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References

1. ITU-T: The Tactile Internet – Technology Watch Report (2014), http://www.itu.int/ITU-T/techwatch
2. Fettweis, G.P.: The tactile internet: Applications and challenges. IEEE Vehicular Technology Magazine 9(1), 64–70 (2014)
3. You, Y., Sung, M.Y.: Haptic data transmission based on the prediction and compression. In: 2008 IEEE International Conference on Communications. IEEE (2008)
4. Holland, O., Steinbach, E., Prasad, R.V., Liu, Q., Dawy, Z., Aijaz, A., Pappas, N., Chandra, K., Rao, V.S., Oteafy, S., Eid, M., Luden, M., Bhardwaj, A., Liu, X., Sachs, J., Araujo, J.: The IEEE 1918.1 "tactile Internet" standards working group and its standards. Proceedings of the IEEE 107(2), 256–279 (2019)

5. ETSI-WP-2017-2018.html, https://www.etsi.org/e-brochure/Work-Programme/2017-2018/mobile/index.html{#}p=28
6. 3GPP – Release 15, https://www.3gpp.org/release-15
7. Standardisation AIOTI, https://aioti.eu/wg_standardisation/
8. Research & Innovation – Next Generation IoT, https://www.ngiot.eu/research-innovation/
9. ICT-56-2020, https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/topic-details/ict-56-2020
10. Gartner Top 10 Strategic Technology Trends for 2020 – Smarter With Gartner, https://www.gartner.com/smarterwithgartner/gartner-top-10-strategic-technology-trends-for-2020/
11. The 5G tactile internet is here. What next? – Ericsson, https://www.ericsson.com/en/blog/2019/4/5g-tactile-internet
12. Deloitte – Top Tech Trends 2021, https://www2.deloitte.com/content/dam/insights/articles/6730{_}TT-Landing-page/DI{_}2021-Tech-Trends.pdf
13. Haddadin, S., Johannsmeier, L., Diaz Ledezma, F.: Tactile robots as a central embodiment of the tactile internet. Proceedings of the IEEE 107(2), 471–487 (2019)
14. Gupta, R., Tanwar, S., Tyagi, S., Kumar, N.: Tactile-internet-based telesurgery system for healthcare 4.0: An architecture, research challenges, and future directions. IEEE Network 33(6), 22–29 (2019)
15. Milasi, S., Gonzalez-Vazquez, I., Fernandez-Macias, E.: Telework in the EU before and after the COVID-19 : where we were , where we head to. Tech. rep. (2020)
16. Aijaz, A., Sooriyabandara, M.: The tactile internet for industries: A review (2019)
17. Van Den Berg, D., Glans, R., De Koning, D., Kuipers, F.A., Lugtenburg, J., Polachan, K., Venkata, P.T., Singh, C., Turkovic, B., Van Wijk, B.: Challenges in haptic communications over the tactile internet. IEEE Access 5, 23502–23518 (2017)
18. Steinbach, E., Strese, M., Eid, M., Liu, X., Bhardwaj, A., Liu, Q., Al-Ja'Afreh, M., Mahmoodi, T., Hassen, R., El Saddik, A., Holland, O.: Haptic codecs for the tactile internet. Proceedings of the IEEE 107(2), 447–470 (2019)
19. Accenture: Tactile Internet Enabled by Pervasive Networks. Tech. rep.
20. Bojkovic, Z.S., Bakmaz, B.M., Bakmaz, M.R.: Vision and enabling technologies of tactile internet realization. In: 2017 13th International Conference on Advanced Technologies, Systems and Services in Telecommunications, TELSIKS 2017 – Proceeding. vol. 2017-October, pp. 113–118. Institute of Electrical and Electronics Engineers Inc. (2017)
21. Prados-Garzon, J., Adamuz-Hinojosa, O., Ameigeiras, P., Ramos-Munoz, J.J., Andres-Maldonado, P., Lopez-Soler, J.M.: Handover implementation in a 5G SDN-based mobile network architecture. In: IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, PIMRC. vol. 0. Institute of Electrical and Electronics Engineers Inc. (2016)
22. Ateya, A.A., Vybornova, A., Kirichek, R., Koucheryavy, A.: Multilevel cloud based Tactile Internet system
23. Joshi, K.C., Niknam, S., Prasad, R.V., Natarajan, B.: Analyzing the Tradeoffs in Using Millimeter Wave Directional Links for High Data-Rate Tactile Internet Applications. IEEE Transactions on Industrial Informatics 16(3), 1924–1932 (2020)
24. Promwongsa, N., Ebrahimzadeh, A., Naboulsi, D., Kianpisheh, S., Belqasmi, F., Glitho, R., Crespi, N., Alfandi, O.: A Comprehensive Survey of the Tactile Internet: State-of-the-Art and Research Directions. IEEE Communications Surveys and Tutorials 23(1), 472–523 (2021)

25. Zhani, M.F., ElBakoury, H.: FlexNGIA: A Flexible Internet Architecture for the Next-Generation Tactile Internet. Journal of Network and Systems Management 28(4), 751–795 (2020)
26. TACTILENet, `https://tactilenet.sabanciuniv.edu/en/Objectives`
27. TACNET 4.0, `http://www.tacnet40.de/index{_}englisch.html`
28. Maier, M., Ebrahimzadeh, A.: Towards immersive tactile internet experiences: Low-latency FiWi enhanced mobile networks with edge intelligence [invited]. Journal of Optical Communications and Networking 11(4), B10 (2019)
29. Neaime, J., Dhaini, A.R.: Resource management in cloud and tactile-capable next-generation optical access networks. Journal of Optical Communications and Networking 10(11), 902 (2018)
30. Luvisotto, M., Pang, Z., Dzung, D.: Ultra high performance wireless control for critical applications: Challenges and directions. IEEE Transactions on Industrial Informatics 13(3), 1448–1459 (2017)
31. Luengas, Y.R., Lopez-Gutierrez, R., Salazar, S., Lozano, R.: Robust controls for upper limb exoskeleton, real-time results. Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering 232(7), 797–806 (2018)
32. Chowdhury, M., Maier, M.: Collaborative Computing for Advanced Tactile Internet Human-to-Robot (H2R) Communications in Integrated FiWi Multirobot Infrastructures. IEEE Internet of Things Journal 4(6), 2142–2158 (2017)
33. Khatib, O., Yeh, X., Brantner, G., Soe, B., Kim, B., Ganguly, S., Stuart, H., Wang, S., Cutkosky, M., Edsinger, A., Mullins, P., Barham, M., Voolstra, C.R., Salama, K.N., L'Hour, M., Creuze, V.: Ocean one: A robotic avatar for oceanic discovery. IEEE Robotics and Automation Magazine 23(4), 20–29 (2016)
34. Wrzesien, M., Botella, C., Bretón-López, J., Del Río González, E., Burkhardt, J.M., Alcañiz, M., Pérez-Ara, M.Á.: Treating small animal phobias using a projective-augmented reality system: A single-case study. Computers in Human Behavior 49, 343–353 (2015)
35. Elbamby, M.S., Perfecto, C., Bennis, M., Doppler, K.: Toward Low-Latency and Ultra-Reliable Virtual Reality. IEEE Network 32(2), 78–84 (2018)
36. Grasso, C., Schembra, G.: Design of a UAV-Based Videosurveillance System with Tactile Internet Constraints in a 5G Ecosystem. In: 2018 4th IEEE Conference on Network Softwarization and Workshops, NetSoft 2018. pp. 132–140. Institute of Electrical and Electronics Engineers Inc. (2018)
37. Tanwar, S., Tyagi, S., Budhiraja, I., Kumar, N.: Tactile Internet for Autonomous Vehicles: Latency and Reliability Analysis. IEEE Wireless Communications 26(4), 66–72 (2019)
38. Cao, H., Gangakhedkar, S., Ali, A.R., Gharba, M., Eichinger, J.: A 5G V2X testbed for cooperative automated driving. In: IEEE Vehicular Networking Conference, VNC. vol. 0. IEEE Computer Society (2016)
39. Wei, X., Duan, Q., Zhou, L.: A QoE-Driven Tactile Internet Architecture for Smart City. IEEE Network 34(1), 130–136 (2020)