TACTILENet

Towards Agile, effiCient, auTonomous and massIvely LargE Network of things

WP4- (Contribution to Standards Activities)

D4.2 D17 Final report on participation in 5G-PPP and Networld2020 affiliated activities.

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Table of Acronyms

Acronym	Expanded form
IT	*Tactile Internet*
HC	*Haptic Codecs*
CFC	*Call For Contributions*
AVB	*Audio Video Bridging*
F2F	*Face-to-Face*
ECUs	*Electronic Control Units*
TSNs	*Time Sensitive Networks*
QoS	*Quality-of-Service*
HIC	*Haptic Interpersonal Communication*
COM/SDB	*Communications Society/Standards Development Board*
IVR	*Immersive Virtual Reality*
KC	*Kinesthetic Codec*
REVCOM	*Standards Review Committee*
QoE	*Quality of Experience*
IMU	*inertial measurement unit*
IoT	*Internet of Things*
ITU	*International Telecommunications Union*

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1. SUMMARY

This report provides an overview of the standardization activities related to Tactile Internet based on the information gathered through publicly available resources, meetings and face-to-face interactions throughout the project duration (M1-M36). The report also provides information on activities of Tactilenet members in different standardization bodies. Note that a part of the material reported in D5.2 overlaps with D5.1, and it is repeated here for completeness. D5.2 provides as new information an overview of activities of a newly formed body in International Telecommunications Union (Section 7). Additionally, D5.2, also provides the overview activities of Tactilenet partners not reported in D5.1.

As reported earlier, standardization activities are usually dominated by industry and directly affecting the outcomes these activities by academia is usually very difficult if not impossible. In this project, we followed these activities closely and participated in the discussions based on the outcomes obtained in WP2 of Tactilenet project. These participations led to improvement of our research activities and introduction of the partners to industry. Several industrial partners have been identified for future collaboration opportunities. Although we were not able to directly affect standards in the lifetime of the project, we believe that our participation have contributed to our future research goals as well as increased our visibility of our consortium as a whole to the industry. Based on this, we believe that the objective of WP4 is partially achieved.

2. INTRODUCTION

By 2020, there will be an estimated 75-100 billion devices that will connect to the Internet, catering to applications like smart homes, body/health monitoring, environmental monitoring, condition-based maintenance, among many others. IEEE Standards Association (IEEE-SA) has recently created a working group to outline the architecture needed to support IoT. Their very first meeting took place in July 2014. IoT's architecture is quite open. This is an opportune time to explore brand new possibilities to influence the standardization efforts.

Significant contributions are expected to the efforts in future "interconnection" standards. Efforts are supposed to further the networking standards for new generation IoT protocols. The following figures, Fig. 1 and Fig. 2, the IoT ecosystem as well as the Network Protocols for IoT are illustrated.

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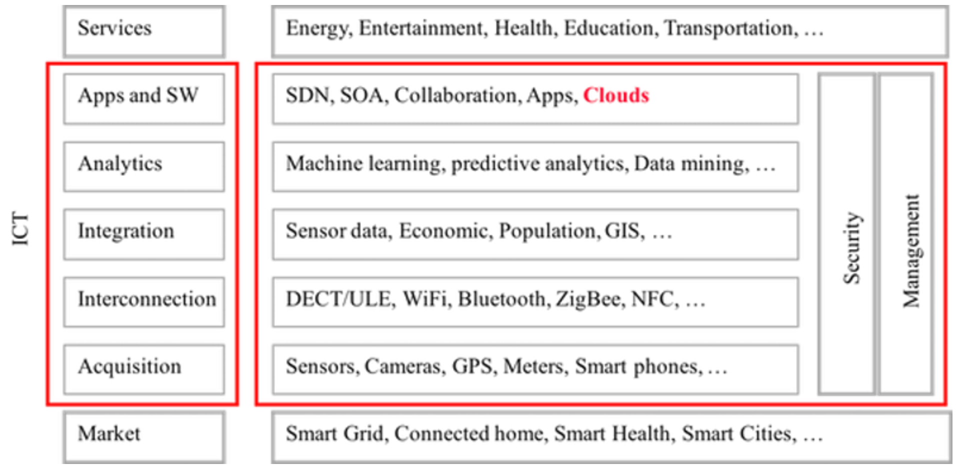

Figure 1 IoT ecosystem

Recently, one promising project called "IEEE P1918.1 Tactile Internet" has been conducted to fulfill these expectations. This project aims to facilitates the rapid realization of the Tactile Internet as a 5G and beyond application, across a range of different user groups. Additionally, this project tries to provide the groundwork upon which the Tactile Internet will be formed. To this end, this project aims to provide a baseline for a pioneering range of further standards that will be created under this working group realizing the key necessary technical capabilities of the Tactile Internet. It defines a framework for the Tactile Internet, including descriptions of various application scenarios, definitions and terminology, functions, and technical assumptions. This framework prominently also includes a reference model and architecture, which defines common architectural entities, interfaces between those entities, and the mapping of functions to those entities. The Tactile Internet encompasses mission critical applications (e.g., manufacturing, transportation, healthcare and mobility), as well as non-critical applications (e.g., edutainment and events). The Tactile Internet presents acutely challenging requirements, in terms of latency, reliability, security, and likely others such as the density of users, devices and links. The Tactile Internet is also highly multi-disciplinary, requiring consideration of aspects outside of the scope of communications technology. While there is broad standardization of 5G technology ongoing under the efforts of the 3GPP, IEEE, ETSI and others, which aim to set the structures in place to realize a range of challenging applications, there are not standards addressing the multi-disciplinary nature of the Tactile Internet or considering the precise challenging mix of requirements that the Tactile Internet entails. This standard, and the following additional standards that will be formed at a later stage under this working group, addresses such aspects.

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Layer		Protocols	Security	Management
Session		**MQTT**, **SMQTT**, **CoRE**, **DDS**, **AMQP** , **XMPP**, **CoAP**, …	TCG, Oath 2.0, SMACK, SASL, ISASecure, ace, DTLS, Dice, …	**IEEE 1905**, **IEEE 1451**, …
Network	Encapsulation	**6LowPAN**, **6TiSCH**, **6Lo**, Thread, …		
	Routing	**RPL**, **CORPL**, **CARP**, …		
Datalink		WiFi, **Bluetooth Low Energy**, **Z-Wave**, **ZigBee Smart**, **DECT/ULE**, 3G/LTE, NFC, **Weightless**, **HomePlug GP**, **802.11ah**, **802.15.4e**, **G.9959**, **WirelessHART**, **DASH7**, ANT+, **LTE-A**, **LoRaWAN**, …		

Figure 2 Network Protocols for IoT

As haptic technologies are becoming increasingly available and diversified, supporting both kinesthetic and tactile interaction in a wide range of applications (tele-operation, gaming and entertainment, automation and robotics, etc.), the need has arisen for the definition of a standard for the compression of haptic data. This is the main target of the Haptic Codecs for the Tactile Internet Task Group within the IEEE P1918.1 Tactile Internet Working Group. This standard defines Haptic Codecs (HC) for the Tactile Internet (TI). These codecs address TI application scenarios where the human is in the loop (i.e. teleoperation or remote touch applications) as well as scenarios that rely on machine remote control. The standard defines (perceptual) data reduction algorithms and schemes for both closed-loop (kinesthetic information exchange) and open-loop (tactile information exchange) communication. These codecs are designed such that they can be combined with stabilizing control and local communication architectures for time-delayed teleoperation. Further, the standard also specifies mechanisms and protocols for the exchange of the capabilities (e.g. workspace, the number of degrees of freedom, amplitude range, temporal and spatial resolution, etc.) of the haptic devices. Tactile Internet applications require standardized haptic codecs that enable interoperability among multiple haptic interfaces. For closed-loop communication, the codecs need to be jointly designed with the control and local communications architecture required for time-delayed teleoperation. For open-loop communication, although the exchange of tactile information is less time critical, it is nevertheless essential to standardize codecs for the emerging tactile sensing and feedback devices (e.g. tactile displays, tactile gloves, etc.).
There are some important notes about the project for clarification:
NOTE 1: The Tactile Internet provides a medium for remote physical interaction which requires the exchange of haptic information.
NOTE 2: Remote physical interaction can apply to humans or machines.
NOTE 3: The term object refers to any form of physical object, including humans.
NOTE 4: For human-in-the-loop physical interaction with haptic feedback this is also referred to as bilateral haptic tele-operation. Ideally, in this case the human user cannot distinguish between locally executing a manipulative task compared to remotely performing the same task across the Tactile Internet.

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NOTE 5: Haptic information refers to either tactile or kinaesthetic information, or both. Tactile information is the information which is perceived by the various mechanoreceptors of the human skin, e.g., of surface texture, friction, temperature. Kinaesthetic information is the information which is perceived by the skeleton, the muscles, and the tendons of the human body, e.g., force, torque, position, velocity. Machines include robots, networked functions, software or any other connected entity.
NOTE 6: For machine-in-the-loop physical interaction the results of the interaction will ideally be the same as if the machines were interacting with objects directly at or close to the locations of those objects.
NOTE 7: The meaning of perceived real time might differ for humans and machines and is use case specific.

The standardization activities of the TI working group and sub-working HC group can be classified into three important aspects including Use Cases, Requirements, and Functional Architecture which are highlighted in the sections II, III, and IV. Also, the related important meetings are briefly discussed in section V. In section VI, all the activities and meetings are summarized in a timeline table. Finally, section VII concludes the report.

3. USE CASES

The working group has categorized the use cases based upon some factors including latency dimension, reliability dimension, loop dimension, and human involvement in the loop. As a summary of outcomes of the group discussions, face-to-face/on-line meetings, and call for contributions (CFC), use cases can be classified as follows:

3.1 Teleoperation over the Tactile Internet

Teleoperation allows human users to immerse into a distant or inaccessible environment to perform complex tasks. A typical teleoperation system, as illustrated in Figure 3, comprises a master (i.e. the user) and a slave device (i.e. the teleoperator), which exchange haptic signals (forces, torques, position, velocity, vibration, etc.), video signals, and audio signals over a communication network. In particular, the communication of haptic information imposes strong demands on the communication network as it closes a global control loop between the user and the teleoperator. For example, the communication delay between the operator and the remote side, jeopardizes the stability of teleoperation and negatively affects the quality of the user. With the advances of the Tactile Internet, teleoperation systems can enjoy the offered ultra-low delay communication services.

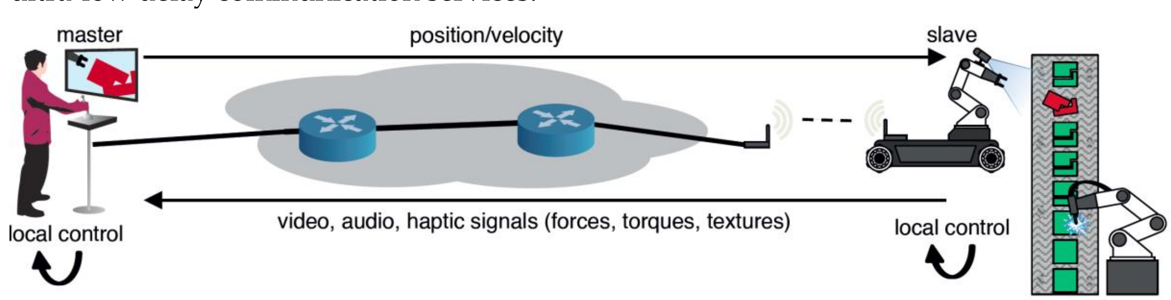

Figure 3 An example of the teleoperation system

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3.2 Internet of Drones over the Tactile Internet

With the unprecedented development of unmanned aerial vehicles (commonly known as drones), the utilization of drones to deliver parcels or vital items (e.g., emergency medicine or medical equipment for patients, and critical urgent components for given tasks), will become possible and will be extensively applied. Already, many innovative firms, such as Amazon, Google, DHL, etc., have already tested the feasibility of drone delivery systems, however, only a very low number of drones have been involved in testing. In a long-term perspective, traffic management for delivery drones (similar to the Air Traffic Control System applied to civil aviation) will be necessary as the scale of usage of drone delivery systems increases. Although drones follow prescribed thoroughly-designed routes, collisions and other conflicts between drones will be inevitable considering that the number of deployed drones is expected to be enormous, with different sets of drones even operated by different companies. As a result, it will be necessary to transmit real-time GPS data, audio data, video data, etc., obtained from various sensors in the drones to a control centre for dynamic route allocation. Moreover, due to the high speed of drones and complexity of the drone delivery system, a low-latency communication network will be required to avoid damage to drones and delivered packages as well as property and human beneath the routes through drone collisions. Built on the Tactile Internet, it will be possible to guarantee the ultra-low latency, efficiency, reliability, and overall safety of the drone delivery system.

In the foreseeable future, drones will be multifunctional and will be capable of completing sophisticated tasks, such as search and rescue for valuable objects or even humans in dangerous places, maintenance and repair of devices located in hard-to-reach places/areas, etc. In this context, humans rather than machines might act as controllers on the master side, with drones acting as slaves. Consequently, not only GPS, audio and video data will be involved, but also haptic (kinaesthetic and tactile) information will be transmitted through the communication network. Compared with the aforementioned drone delivery system example, this might have different demands for latency due to the characteristics of humans as sinks of the information. Moreover, machines might also be sinks in such complex tasks—performing the operation in an automated way. Machines as clients/users of the information and controllers of the drones might have very challenging latency requirements indeed. Undoubtedly, the use of the Tactile Internet to satisfy such situations is appropriate.

3.3 Automotive Use Case for the Tactile Internet

Future cars require a permanent connectivity with other cars and infrastructures to handle life-critical situations to reduce the mortality rate globally. Vehicular sensing data used by the driver to make improved decision during driving events need to be transmitted in real-time with almost zero delay. New remote driving scenarios will further increase the demand for low-latency networks and are in the focus of the Tactile Internet. In-vehicular networks are currently standardized within the IEEE 802.1 (IEEE 802.1BA, IEEE 802.1AS, IEEE 802.1Qat, IEEE 802.1Qav) and consider trends in automotive high speed networks and ultra-low latency requirements. These requirements are driven by adding new applications into the vehicles such as high-

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resolution cameras (4K, 8K) and sensors with high data rate volume. Such high data volume is used within the vehicle to support the driver in life-critical driving situations. To reduce the latency between the Electronic Control Units (ECUs), the IEEE 802.1 suggested new Ethernet standards particular in vehicular networks. Automotive Audio-Video Bridging (AVB) and Time Sensitive Networks (TSNs) are soon to be standardized and will allow new enhanced applications for remote control of driving functions that may be based on sensor-fusion of in-vehicular sensing data with outside sensing data. The upper boundary of in-vehicular network delay is targeted below 1 ms.

In addition to the well-known master-slave model, the IEEE 802.1 suggested to standardize a more sophisticated communication model that uses *talker* and *listener*. It is more flexible, because multiple ECUs in a single vehicle may receive the same content from a single or multiple talkers. In addition, a listener may change its behaviour and provide data, thus operating as a talker and vice-versa. To support the upper latency boundaries, the *edge* unit may be relevant to support local decision making among cars or within vehicular fleets (5G networks), see Figure 4. Such ultra-low latency is required to fulfil driver expectations for a spontaneous driving event.

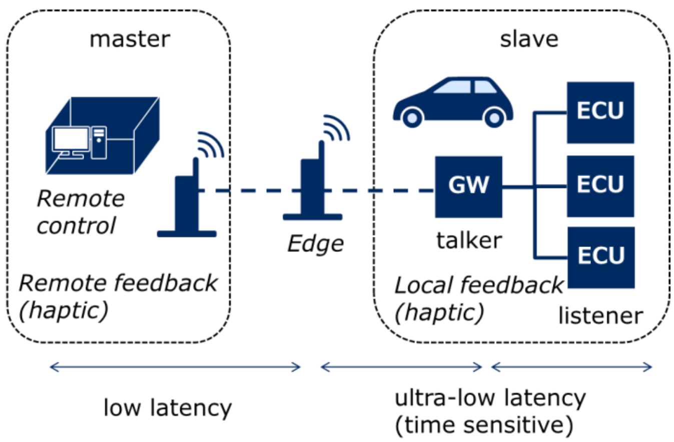

Figure 4 Network scenario for the automotive use case

New haptic applications may target the remote driving support of shuttles, trucks, and road machines in areas which are hard to serve or difficult to maintain. Remote driving requires spontaneous feedback, including haptic events, to make reliable decisions in life-critical situations.

3.4 Interpersonal communication over the Tactile Internet

Human touch of various forms including handshake, pat, or hug is fundamental to physical, social, and emotional development of humans. For instance, in close relationships such as family and friends, touch plays a prominent role for affective communication. Haptic Interpersonal Communication (HIC) enables mediated touch (kinesthetic and/or tactile cues) over a computer network to feel the presence of a remote user and to perform social interactions. The application spectrum for HIC

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systems extends from social networking, gaming and entertainment to education, training, and health care.

A typical HIC system is illustrated in Figure 5. The system comprises a local user, a remote participant, a remote participant model at the local environment, and a local user model at the remote environment. Maintaining a human model for remote use involves the exchange of haptic data (position, velocity, interaction forces, etc.) and non-haptic data (gestures, head movements and posture, eye contact, facial expressions, etc.). The system supports two types of interactions: dialog interaction involves affecting the remote participant presence whereas observing interaction includes perceiving the remote participant presence. Note that the human models (remote participant or local user) can be either a physical entity (such as a social robot) or a virtual representation (such as a virtual reality avatar). With the advances of the Tactile Internet, interpersonal communication systems can enjoy high level of co-presence via the offered real-time, ultra-reliable communication services.

The quality-of-service (QoS) requirements and the capabilities of HIC systems vary considerably with the dynamics of the interaction with the remote participant. In the dialoging mode where the interaction is highly dynamic (e.g. therapist-patient interaction, where the therapist remotely operates a local robotic avatar to assist the local patient perform rehabilitation exercises), delays and reliability of haptic data communication is paramount for safe communication (a latency requirement of 0-50 ms). For the observing mode where interaction is static or quasi-static (e.g. Tele-training system, where a trainee will be observing the performance of a remote trainer), the latency requirement can be further extended to 0-200 ms.

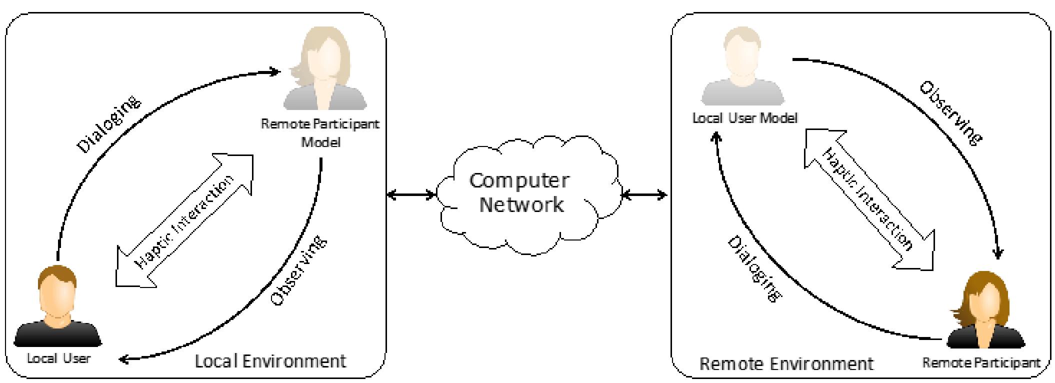

Figure 5 Haptic Interpersonal Communication System

3.5 Live Haptic Enabled Broadcasts over the Tactile Internet

"Immersive", "Personalized", "Virtual Reality", "Second Screen", "Over-the-Top Content", "TV Everywhere" are the words now being used to describe the new ways to create, produce and distribute all types of content to consumers. Continuing advances in picture quality, now up to "4K" with "8K" not far behind, streaming of post produced and live content, including sports, new audio formats, growing interest in and increasing adoption of Virtual Reality, combined with viewers at home and on the go using their smart phones and tablets as their primary or "second screen" for watching TV, are creating challenges and opportunities for new technologies to come

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online to give consumers the type of personalized and immersive experience they are looking for. However, even with all these advancements in video and audio essence, there is still one important aspect missing, the ability to let the viewer actually "feel", "sense" or "perceive" the on-screen action creating a truly immersive and personalized experience.

Haptic-tactile broadcasting is the end to end use of technology to capture, encode, broadcast – transmit, transport, by any means - decode, convert and deliver the "feeling" or "impact" or "motion" of a live event so that a remote viewer can experience the same haptic-tactile experience of the broadcast event. It is the addition of this third essence type, haptics, in addition to the capture and transmission of the audio and video essences that make haptic-tactile broadcasting different from traditional broadcasts.

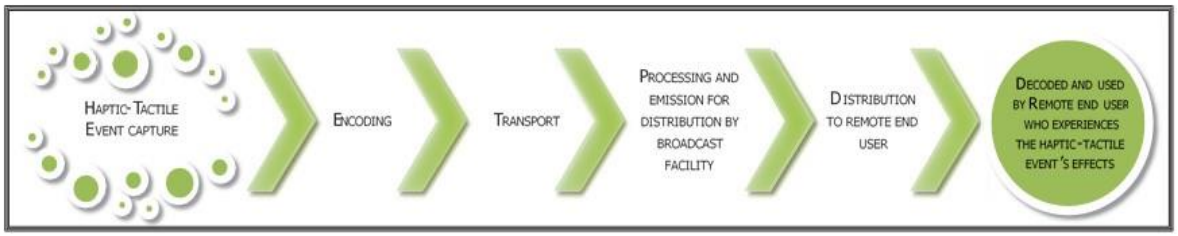

Figure 6 Live Haptic Enabled Broadcast Flow Chart

Purpose of this usecase is to provide the means for haptic-tactile essence to be transported or transmitted as an integral part of a live broadcast event that is distributed to the end user over the internet.

1) Use Case Ecosystem: For the end user, whether at their home, at a sporting venue, cinema or other location, the haptic-tactile data is decoded and converted into a digital or analog signal that is used by the appropriate electro-mechanical haptic-tactile consumer electronics hardware so that the end user can experience substantially the same haptic-tactile effects as the event's original haptic-tactile event. Haptic-tactile broadcast signals can be decoded and used by a wide range of Consumer Electronics (CE) devices including home theatre systems, home theatre seating, gaming consoles, personal computers, mobile handsets, televisions, set-top-boxes, virtual reality headsets and systems, wearable devices, IoT enabled devices, haptic enabled cinema seats or other such devices are used to provide the end user's own haptic-tactile experience, in conjunction with their existing audio and video system.

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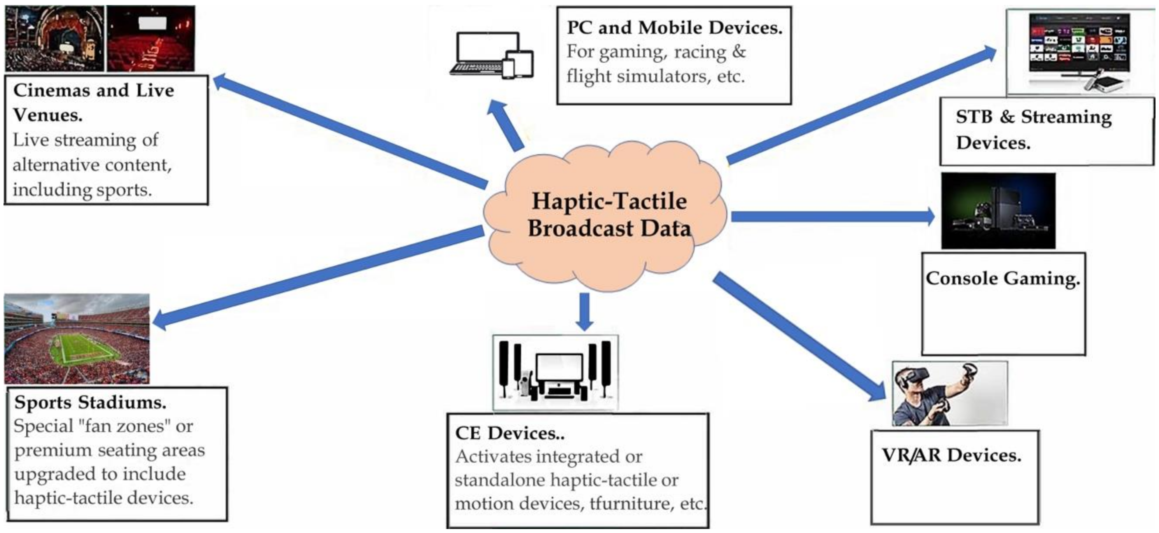

Figure 7 Live Haptic Enabled Broadcast End User Device Ecosystem

2) Typical Live Haptic Enabled Broadcast Production Workflow: Figure below provides a relatively detailed overview of the entire haptic-tactile broadcast process from the point the haptic-tactile data is captured from an event, all the way to being used by the end user in a traditional broadcast environment.

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Figure 8 Live Haptic Enabled Broadcast Work Flow–Traditional or Linear Model. (IP Distribution to the End User Assumed)

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3.6 Immersive Virtual Reality

Immersive Virtual Reality (IVR) describes the case of a human interacting with virtual entities in a remote environment such that the perception of interaction with a real physical world is achieved. Linked to the emergence of helmet-mounted VR devices such as Oculus VR, HTC Vive, PSVR, and Microsoft Hololens, among others, there is a burst of VR applications and interest in the entertainment industry, especially in the fields of VR video and VR Gaming. Expanding this, IVR systems have already been applied or have enormous potential to be utilized in the numerous areas. These include:

1) <u>Education:</u> It is clearly more interesting for the student if he/she can (physically) interact with what they are learning rather than just reading a text or viewing video. Further, IVR systems can also enhance students' concentration since there are no distractions in the virtual world.

2) <u>Health Care:</u> IVR systems can not only provide innovative approaches for therapy (e.g., treating mental illness), but can also contribute to rehabilitation programs from physical diseases. There are various research studies showing that IVR is very helpful for rehabilitation of post-stroke patients, for example.

3) <u>Training:</u> The utilization of IVR systems to train drivers, pilots and surgeons, for example, will lead to entirely safe training.

The degree of immersion achieved in IVR indicates how real the created virtual environment is. Even a tiny error in preparation of the remote environment might be noticed, as humans are quite sensitive when using VR systems. Therefore, a high-field virtual environment (high resolution images, and 3D stereo Audio) is essential to achieve an ultimately immersive experience. Moreover, a key point of interest to the Tactile Internet as a platform for IVR is latency. In order to avoid simulator sickness, motion-to-photon delay (the time difference between user's motion and corresponding change of the video image on display) should be less than 25ms. To date, the best motion tracking system consists of an inertial measurement unit (IMU) and camera-based capture system, and causes 1 ms tracking latency, while the rendering latency and display latency are expected to be about 16ms. Consequently, the communication latency for IVR over the Tactile Internet must be less than 10 ms. Moreover, some research studies show that the latency requirement can be tougher (e.g., around 7 ms) for some extreme scenarios. As a result, the Tactile Internet with ultra-low latency is a quite appropriate platform for IVR systems. Users are supposed to perceive all 5 senses (vision, sound, touch, smell, gustation) for full immersion in the virtual environment. However, most IVR systems only provide conventional controllers (e.g., PlayStation Controllers for PSVR) or some simple haptic controllers (e.g., the DUALSHOCK4 for the PSVR can only trigger monotonous vibrations). There is no doubt that more and more complex haptic (both kinaesthetic and tactile) components will be integrated to IVR systems to significantly enhance the degree of immersion. The data size of the IVR systems is already huge due to the high-degree

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Field of View (FoV) imitating the human's visual capabilities. The addition of haptic data will dramatically expand the total data size, thereby reducing the latency requirement further since data reduction will take longer. Built on the Tactile Internet, it will be possible to restrict the communication latency to the required low value, and also guarantee the stability and degree of immersion of the IVR system.

3.7 Cooperative Automated Driving over the Tactile Internet

Currently, most self-driving vehicles rely on single-vehicle sensing/control functionalities, which have limited perception/maneuvering performance. Without cooperation, in fact, the field of perception of the vehicle is limited to the local coverage of the on-board sensors. Furthermore, having no knowledge on how neighbouring vehicles will behave, the automated control system needs to allocate a safety margin into the planned trajectory that in turn reduces the traffic flow. To guarantee safety and traffic efficiency at the same time, especially in envisioned scenarios with high density of self-driving vehicles, a paradigm shift is required from single-vehicle to multi-vehicle perception/control. This will be enabled by the Tactile Internet for vehicle-to-vehicle/infrastructure (V2V/V2I) or vehicle-to-any (V2X) communications.

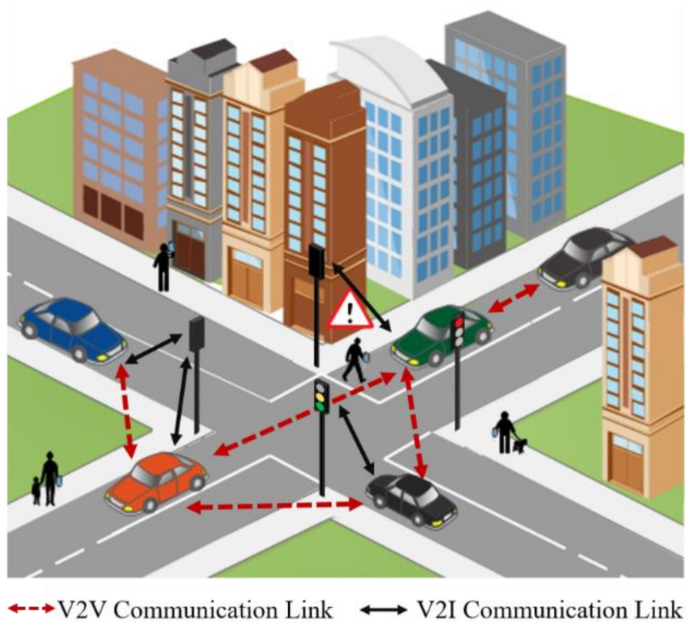

Figure 9 Vehicular network scenario for the cooperative automated driving use case.

Tactile Internet V2X enables fast and reliable exchange of highly-detailed sensor data between vehicles, along with haptic information on driving trajectories, opening the door to the so called cooperative perception and maneuvering functionalities. An example of networked autonomous vehicles is illustrated in Figure 9. By the Tactile Internet connectivity, vehicles can perform a cooperative perception of the driving environment based on fast fusion of high-definition local and remote maps collected by the on-board sensors of the surrounding vehicles (e.g., video streaming from

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camera, radar or lidar). This allows to augment the sensing range of each vehicle and to extend the time horizon for situation prediction, with huge benefits for safety [6]. Furthermore, in cooperative maneuvering, continuous sharing and negotiation of the planned trajectories allows the vehicles to synchronize to a common mobility pattern [5]. Since the uncertainty on the neighbouring vehicles' dynamics is reduced, the space headway can be lowered in safety forming tight autonomous convoys, with clear benefits in traffic efficiency.
Existing V2X standards (i.e., IEEE 802.11p/WAVE and ETSI ITS-G5) support driver assistance and partial automation services, but they are not able to cover the requirements for higher levels of automation. As shown in Table 1 for first generation (1G) V2X, their data rate is limited to 3-27 Mb/s (only exchange of highly aggregated information is supported), the message update rate is 10 Hz, and the end-to-end (E2E) latency ranges from 100 ms down to 20 ms [8,9,10]. These performances cannot meet the requirements of cooperative automated driving, where the smaller inter-vehicle spacing and the repeated data exchange puts higher demands in terms of latency, data-rate and reliability (see Table 1). A latency of 1-10 ms is needed for realizing the stable control of a convoy of vehicles. The data-rate for cooperative perception ranges from few tens of Mb/s up to 1 Gb/s (in perspective), depending on the resolution of the exchanged maps. Note that on-board sensors in today self-driving cars generate data flows up to 1 GB/s.

4. CONSOLIDATED USE CASES CHARACTERISTICS

Use case / scenario	Traffic direction	Traffic types	Burst size	Reliability (%)	Latency (ms)	Average data rate
Immersive Virtual Reality	Slave → Master (Users → IVR system)	Haptic feedback	Kines./tactile sigs. 1 DoF: 2-8 B 3 DoFs: 6-24 B 6 DoFs: 12-48 B	99.9 (w/o compr.) 99.999 (w/ compr.)	<5	1-4k pkts/s (w/o compr.) 100-500 pkts/s, (w/ compr.)
	Master → slave	Video	1.5 kB	99.999	<10	1-100 Mbps
		Audio	100 B	99.9	<10	5-512 kbps
		Haptic feedback	Kines./tactile sigs. 1 DoF: 2-8 B 3 DoFs: 6-24 B 6 DoFs: 12-48 B	99.9 (w/o compr.) 99.999 (w/ compr.)	1-50	1-4k pkts/s (w/o compr.) 100-500 pkts/s, (w/ compr.)
Tele-operation	Master → Slave	Haptics	1 DoF: 2-8 B 3 DoFs: 6-24 B 6 DoFs: 12-48 B	99.999	1-10 (high dyn. environ.) 10-100 (dyn.)	1-4k pkts/s (w/o compr.) 100-500 pkts/s (w/ compr.)
	Slave → Master	Video	1.5 kB	99.999	10-20	1-100 Mbps
		Audio	50 B	99.9	10-20	5-512 kbps
		Haptic feedback	Tactile sigs. 1 DoF: 2-8 B	99.999	1-10	1-4k (w/o compr.)

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			10 DoFs: 20-80 B 100 DoFs: 200-800 B			100-500 (w/ compr.)
Automotive	Master → Slave	Haptics (pos., veloc., ang. veloc., decel., accel.)	2 kB	99.9 (w/o compr.) 99.999 (w/ compr.	1-10 (life-critical, high-dyn. environ.) 10-100 (med.-dyn.) 100-1000 (stat. or quasi-stat.)	100-2000 pkts/s (w/o compr.) 100-500 pkts/s, (w/ compr.)
	Slave → Master	Video	2 kB- 4 kB	99.9	1-10 (high-dyn. environ.) 10-100 (med.-dyn.) 50-150 (stat. or quasi-stat.)	1-10 Mbps
		Audio	100 B	99.9		100-500 kbps
		Haptic feedback (forces, trqes, vib'tact. sigs.)	1 DoF: 2-8 B 10 DoFs: 20-80 B 100 DoFs: 200-800 B	99.9 (w/o compr.) 99.999 (w/ compr.)	1-10 (high-dyn. environ.) 1-10 (med.-dyn.) 1-10 (stat. or quasi-stat.)	100-500 pkts/s (w/o compr.) 100-500 pkts/s, (w/ compr.)
Internet of Drones (with humans; without humans latency require-ment even more stringent)	Master → Slave	Haptic feedback	Kines./tactile sigs. 1 DoF: 2-8 B 3 DoFs: 6-24 B 6 DoFs: 12-48 B	99.9 (w/o compr.) 99.999 (w/ compr.)	2.5-5 (kines.) 50-100 (tactile)	1-4 k pkts/s (w/o compr.) 100-500 pkts/s, (w/ compr.)
	Slave → Master	GPS	2 kB	99.9	30-40	1-20 Mbps
		Video	4 kB	99.999		1-100 Mbps
		Audio	50 B	99.9		5-512 kbps
		Haptic feedback	Kines./tactile sigs. 1 DoF: 2-8 B 3 DoFs: 6-24 B 6 DoFs: 12-48 B 10 DoFs: 20-80 B 100 DoFs: 200-800 B	99.9 (w/o compr.) 99.999 (w/ compr.)	2.5-5 (case dependent)	1-4k pkts/s (w/o compr.) 100-500 pkts/s (w/ compr.)
Inter-personal Communica-tion	Participant 1 ↔ Participant 2	Video	1.5 kB	99.999	10-20	1-100 Mbps
		Audio	50 B	99.9	10-20	5-512 kbps
		VR	MTU	99.9	50	600 Mbps
		Haptic	Tactile sigs. 1 DoF: 2-8 B 10 DoFs: 20-80 B 100 DoFs: 200-800 B	99.999	1-10 (for interaction) 100-1000 (for observation)	1-4k pkts/s (w/o compr.) 100-500 pkts/s, (w/ compr.)
Live Haptic-Enabled Broadcast	N/A	Video	See ATSC 3.0		NA	See ATSC 3.0
		Audio	See ATSC 3.0		NA	See ATSC 3.0

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		Haptic	TBD		12-18	See ATSC 3.0
Cooperative Automated Driving	Slave → Master	Haptic (pos., vel., accel., pre-proc. sens. data)	~50-1200 B	99.999	1-10	<10 Mbps
	Master → Slave	Video (raw radar, lidar, cam. data)	~2-4 kB	99.9	10-50	10-40 Mbps

5. REQUIREMENTS

5.1 Haptic Codecs Requirements

1) Handshaking Protocols: The handshaking protocol should include the syntax for requests, responses and registration. The request mechanism initiates communication between two haptic devices for establishing, controlling and terminating sessions. The response mechanism handles the result of a received request. The registration mechanism conveys IP-like address information of devices, which may be handled by a server (or broadcasted over the network if the connections are in an ad-hoc manner). Additionally, it is responsible for the capabilities of exchange of meta data.

2) Kinesthetic Codecs: Kinesthetic codecs are developed to support stable and perceptually transparent teleoperation with (or without) communication delay. The codec should be able to reduce the packet rate without introducing significant perceivable distortion, that is, maintaining transparency.

3) Tactile Codecs: The exchange of tactile information is less time critical, compared with the kinesthetic counterpart. Therefore, the challenge of tactile codecs lies in the data modeling and compression. The structure of the codec should be independent of how the tactile signals are represented. For example, we should be able to represent tactile information at any position of the explored object surface with respect to time as F (x; y; t) where (x; y) defines a particular point at the surface. In addition, the tactile codec should explore the spatial similarity of tactile values between a given position (i.e. single-point) and its neighboring positions (multi-point).

5.2 Requirements of Designing Quality Evaluation Metrics

1) Subjective Quality Evaluation: The subjective methodology is specially designed for the reference software/hardware. It is noted that the following requirements will not be standardized in the Haptic Codec standards, but will contribute to the development of handshaking protocols, kinesthetic codecs, tactile codecs, and subjective and objective quality evaluation metrics. In order to be able to evaluate and compare competing haptic codec proposals and to optimally parametrize them, reproducible subjective experiments need to be developed. The subjective

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tests should be designed such that the quality of interaction, the perceivability of coding artefacts, etc. can be determined. For that purpose, psychophysical experiments need to be set up. There are many psychophysical tests available such as 1I-2AFC (one interval-2 alternative forced choice), 2I-2AFC, 3AFC, etc. Results can be analyzed based4 on modern (signal detection theory) as well as classical psychophysical methods. The following performance metrics should be evaluated for haptic codecs with different data reduction rates and different communication delay requirements: 1) stability; 2) task performance; 3) user experience; 4) system transparency (as a function of control algorithm and communication delay); 5) asynchrony of audio, video and haptic modalities. In order to validate the significance of the subjective observations, statistical hypothesis tests such as z-test, t-test, F-test, Wilcoxon singed rank test, ANOVA, etc. need to be applied with a defined confidence interval for example 95 percent.

2) Objective Quality Evaluation: Identifying the objective (quantitative) system performance metrics will allow to quickly determine the best data reduction parameters, the best-suitable control schemes and the key communication requirements (e.g. tolerable delay, requested transmission rate, etc.) in haptic codecs. The objective quality metric should mimic the results obtained through subjective evaluation.

5.3 Implementation Requirements

1) Reference Software: The reference software should be able to easily integrate to the reference hardware setup defined in the next section. It should also include the main functionalities of both kinesthetic and tactile codecs for haptic communication. A network emulator can be suggested and then used together with the reference software to mimic the communication network between the master and the slave.

2) Reference Hardware: The reference hardware should be a teleoperation system which consists of off-the-shelf hardware components and integrates the main functionality of the reference software and the handshaking protocol. The reference hardware should contain the part list, the specifications, the setup guidelines as well as the instruction manual. The intention is to provide the community with a build-your-own-teleoperation-system-in-one-day solution and run it over the network (e.g. Ether-net).

3) Audio/Video/Haptics Multiplexing: An efficient mechanism should be developed to multiplex different traffic modalities. It is important that the developed multiplexing mechanism will not violate the delay-constraints of haptic codecs defined in the above sections.

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6. FUNCTIONAL ARCHITECTURE

The end-to-end functional architecture comprises three distinct domains. Information exchange is bi-directional and usually closes a global control loop (haptic vs. non-haptic control).

6.1 General Architecture

The general Tactile network end-to-end functional architecture is illustrated in Fig. 10.

Master/Device Domain

The master domain controls the operation of the slave domain. In most applications, it consists of a human (operator) and a human system interface, which converts human input into a tactile input. It has the provisioning for auditory and visual feedbacks. Also, human element will be replaced by a controller and multiple operators can collaboratively control the operation of a single slave domain.

Slave/Controlled Domain

In most applications, it consists of a remote operator which interacts with various objects in the remote environment. No a priori knowledge about the environment exists. In some applications, multiple operators can collaboratively control the operation of a single slave domain. Also, it has the provisioning for auditory and visual feedbacks and it consists of a sensor-actuator system.

Network Domain

The network domain (WAN, LAN, etc.) provides the medium for bi-directional information exchange between master and slave domains. The network domain must fulfill the key technical requirements. 5G networks will enable the Tactile Internet at the wireless edge. Also, network slicing, enabled by NFV/SDN, will provide the required design flexibility.

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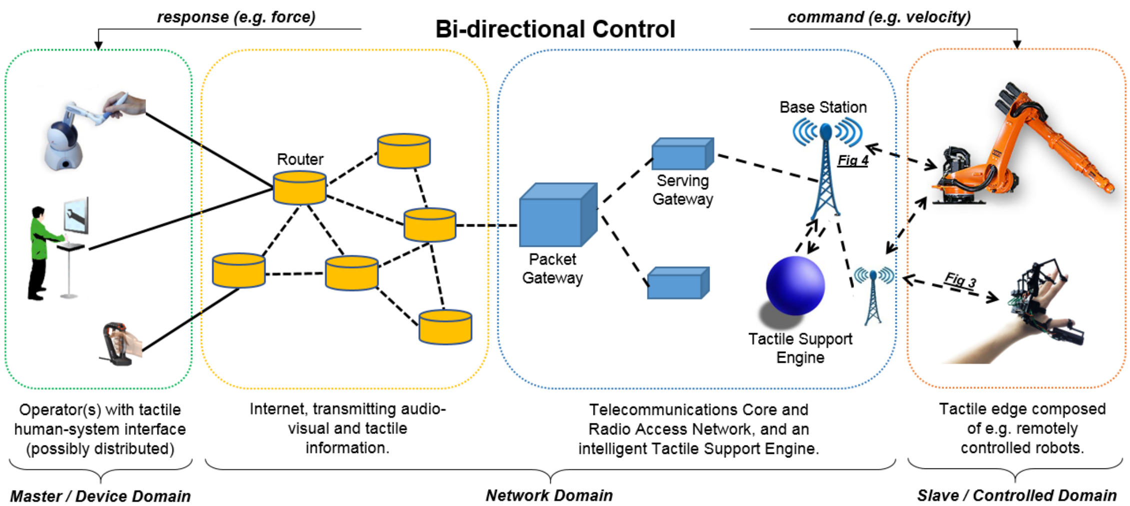

Figure 10 End-to-End Functional Architecture

6.2 Consolidated Reference Architecture

The consolidated reference architecture including functional description, key interfaces and protocol stack are illustrated in following figures:

1) Consolidated Reference Architecture I and Interfaces:

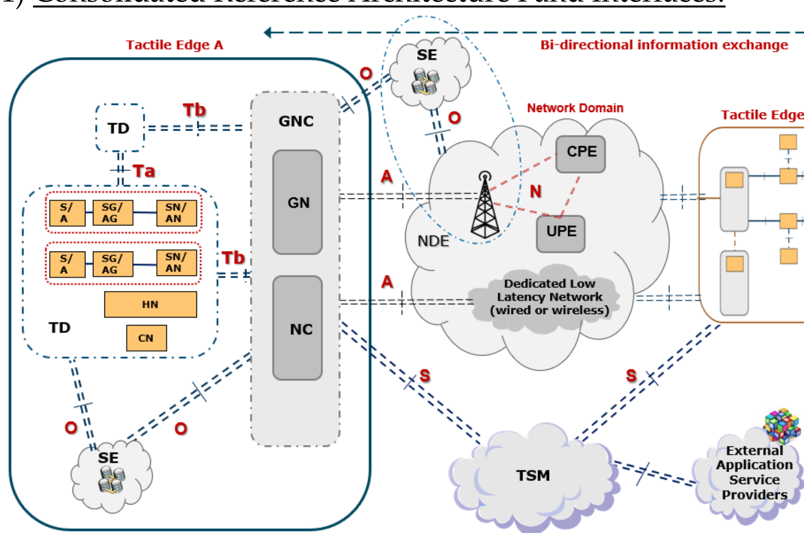

Figure 11 Consolidated Reference Architecture I and Interfaces:

2) Consolidated Reference Architecture II and Interfaces:

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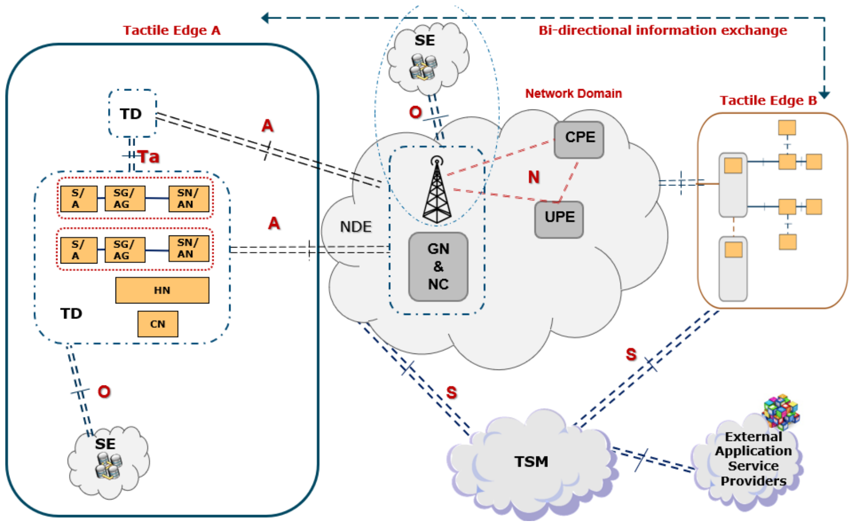

Figure 12 Consolidated Reference Architecture II and Interfaces:

3) <u>Reference Architecture I: Protocol Stack:</u>

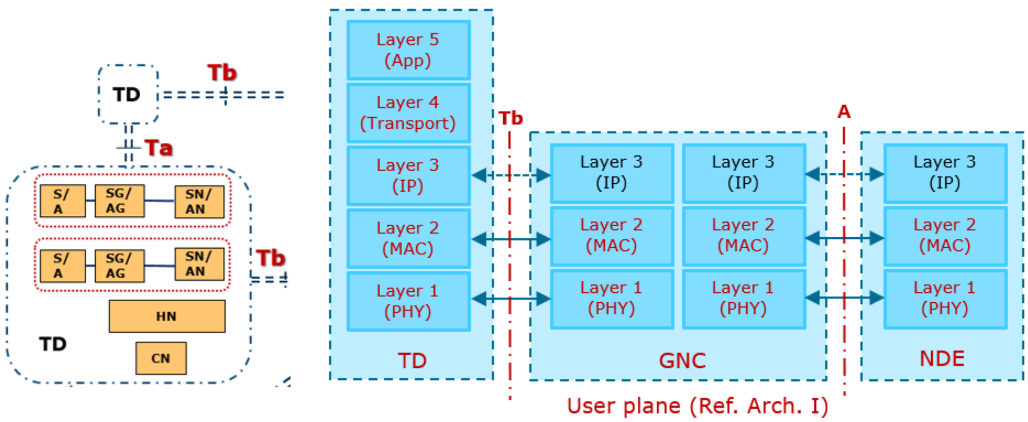

Figure 13 Reference Architecture I: Protocol Stack

4) <u>Reference Architecture II: Protocol Stack:</u>

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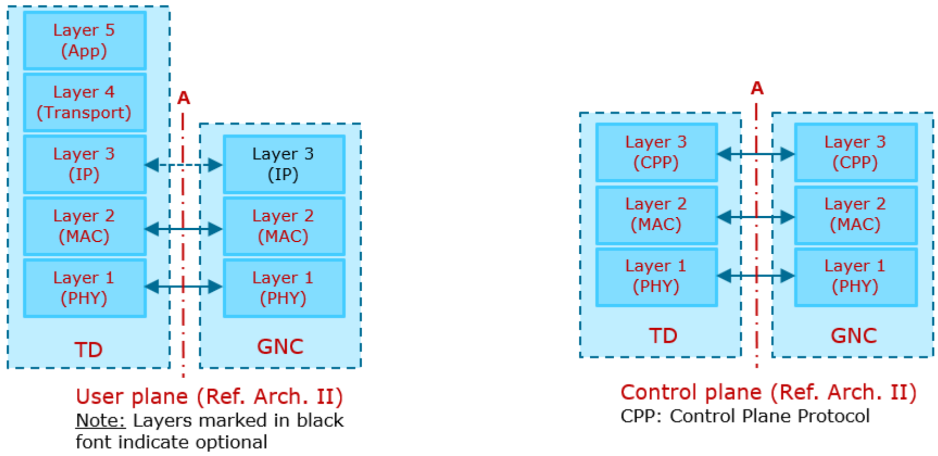

Figure 14 Reference Architecture II: Protocol Stack

5) Reference Architecture: Ta Protocol Stack – Data Transmission Mode:

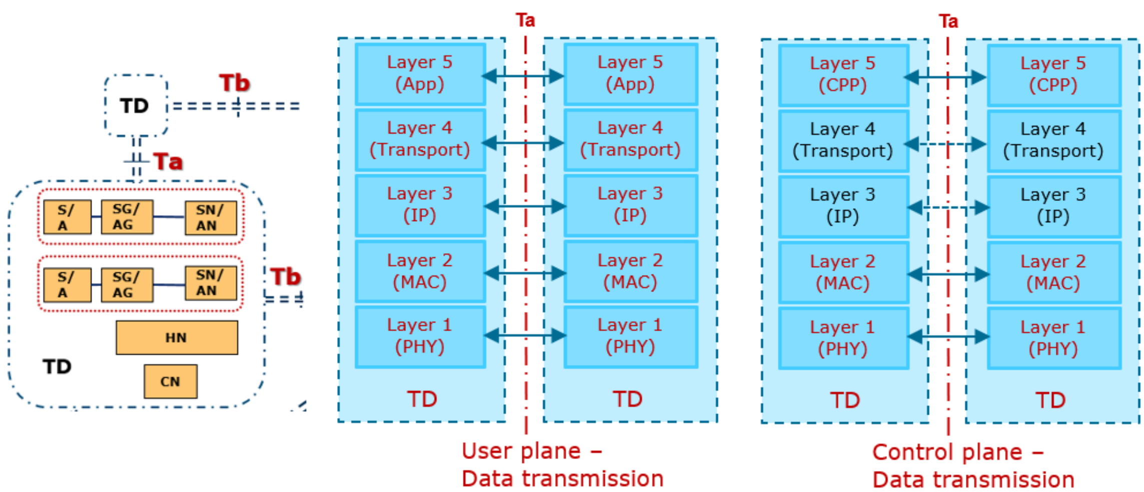

Figure 15 Reference Architecture: Ta Protocol Stack – Data Transmission Mode

6) Reference Architecture: O & S Protocol Stack (end-to-end):

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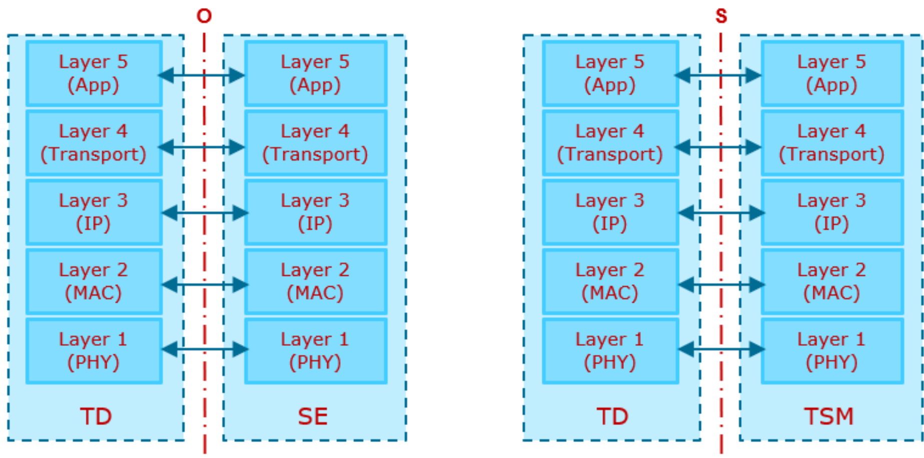

Figure 16 Reference Architecture: O & S Protocol Stack (end-to-end):

6.3 Proposed Modifications to the Consolidated Architecture

1) Issues in the Current Consolidated Architectures:
   - The proposed architectures requires that the network infrastructure to guarantee the tactile requirements (latency, reliability)
   - Incorporating haptic codecs in the current architectures is not clear
   - The Network Controller (NC) seems to be doing both control and data information exchange
   - The functionality of the NC needs to be defined precisely
2) Proposed Modifications:
   - Every Tactile Device (TD) can have the following components[1]:
   - Tactile Application Manager (TAM)
   - Tactile Local Network Manager (TLNM)
   - TAM consists of Application Monitor (AM) and Application Controller (AC)
     i. AM monitors the application level (or end-to-end) QoE/QoS
     ii. AC incorporates intelligent/AI/haptic codec algorithms, and adapts based on inputs from AM
   - TLNM consists of Local Network Monitor (LNM) and Local Network Controller (LNC)
     i. LNM monitors the performance of the local network from TD to the GN
     ii. LNC incorporates algorithms at MAC/LLC/network layers of the networking stack to adapt/optimize the network performance
   - Replace the current NC with Tactile Network Manager (TNM)
   - TNM consists of Network Monitor (NM) and Network Controller (NC)

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i. NM monitors the performance of the current network between peer(s) NM
ii. Additionally, if multiple network connectivity options are available, the NM needs to also monitor them
iii. NC incorporates algorithms at the network and higher layers of the networking stack to adapt/optimize the network performance
iv. Additionally, NC may also incorporate algorithms to switch/fallback to a better network if the performance is unsatisfactory

7. IEEE 1918.1 STANDARDIZATION ACTIVITIES

7.2 Important Meetings

Kick-Off Meeting

The 1st Working Group Meeting was held in Kuala Lumpur, Malaysia where the group discussed the roadmap, terms and definitions of the standard and scheduled the upcoming online and face-to-face meetings.

First f2f meeting

The project's first face-to-face meeting was held close to the IEEE GLOBECOM 2016 conference in Fairfax, VA, USA. The project called for Participation in Haptic Codecs for the Tactile Internet Sponsored by IEEE Communications Society/Standards Development Board (COM/SDB) Within the IEEE Tactile Internet Working Group. They mainly discussed on the introduction to the sub-working group and the scope, objectives, and the approved PAR of the Haptic Codecs (HC) standard and also introduction and explanation of tools that will assist their standard development.

HC f2f meeting

The first face-to-face meeting of Haptic Codec Task Group (P1918.1.1), was held on 9-10 March 2017, Abu Dhabi where they presented the requirements of Haptic Codecs, which were proposed and approved during the first face-to-face meeting of the TI working group.

Munich Meeting

IEEE P1918.1.1 HC Task Group 2nd face-to-face meeting was held on 10 June 2017, in Technical University of Munich, Munich, Germany where they reviewed the requirements for Haptic Codecs, discussed on the CfC and continued on discussing and drafting the CfC. Also, they discussed on future meetings - objectives and draft agenda.

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7.2 Timeline of Activities

The following table summarizes the meetings and the activities of the TI working group and sub-working HC group which has been classified in a timeline from the beginning of the work to the completion and submission of their final draft with a short description:

Date	Objective
September 2016	Completion of key terms and definitions that are vital to the realization of our Tactile Internet standard.
April 2017	Steady-state view of key use cases and requirements. Approval by working group based on text contributions to draft standard. Doesn't limit possible future additional use cases.
July 2017 (Face-to Face)	Steady-state view of system architecture prepared: entities, interfaces between those entities and natures of those interfaces. Completion of first text contribution thereof.
May 2018	Functional architecture: the attribution of functions to entities and detailed descriptions of functions in terms of their scopes/responsibilities.
July 2018	Interfaces: Definition of message sequence charts (?) and information structures for interfaces (TBD the level of detail it is appropriate to cover here…?).
October 2018	Steady-state view on definition of functional capabilities, e.g., artificial intelligence supporting the Tactile Internet?
Start in October 2017 working towards February 2019	Intensive work on finalization of draft integrating content prepared according to above deadlines; cross-checking technical aspects (e.g., consistency), styles/content, completeness of information, etc.

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8. ITU FOCUS GROUP FOR NETWORK 2030 (FG NET-2030)

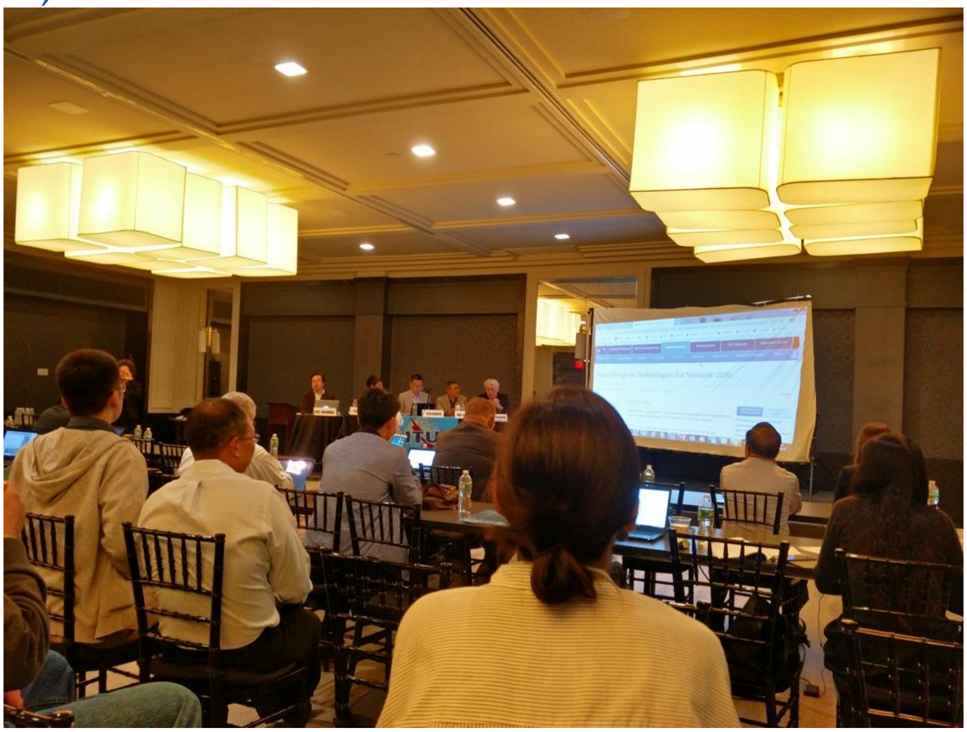

Figure 17 ITU FG Net2030 Meeting in New York, NY September 2018.

Tactilenet consortium have become aware of the standardization activities of International Telecommunications Union (ITU)'s focus groups and started active participation of the meetings in the period after the midterm report.

The Focus Group for Network 2030 (FG NET-2030), intends to study the capabilities of networks for the year 2030 and beyond, when it is expected to support novel forward-looking scenarios, such as holographic type communications, extremely fast response in critical situations such as autonomous driving and high-precision communication demands of emerging market verticals. The FG-NET-2030, as a platform to study and advance international networking technologies, will investigate the future network architecture, requirements, use cases and capabilities of the networks for the year 2030 and beyond. It will be further realized by the exploration of new communication mechanisms from a broad perspective and is not restricted by existing notions of network paradigms or to any particular existing technologies, which may result in quite different than today's networks. However, the future network shall ensure they remain fully backward compatible, supporting both existing and new applications.

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Over the years use cases driving technologic developments will have high requirements: 1) Higher bandwidth / throughput to carry ever larger amount of data (e.g. holographic communication > 1 Tbps per person) 2) Low latency (e.g., autonomous driving < 1 us) 3) Scalability to ever increasing number of devices. Current network architecture and protocols are kind of statistical multiplexing-based technologies which provide best-effort but limited quality of service (QoS) guarantees. Furthermore, they focus on deterministic bandwidth and service as well lack of control over delay, inappropriate for large scale network. Since IP layer is the only interface between user and network and the network is not aware of the needs of application layer, users cannot express the experience quality for the network, and therefore the network is unable to provide heterogenous services. Thus, existing structures will undoubtedly fail to satisfy these heterogenous and increasingly demanding requirements. First step to address this aforementioned inadequacy of existing network protocols is to collect accurate, real-time and complete network status data and responds accordingly in timely fashion. For example, mapping between hostname (or other entitle) into IP is time-cost and lost the original meaning IP addresses can be forged and mapped wrongly and mappings are frequently changed and difficult to trace. In addition, main issues raised by fixed protocol fields such as in IP is meaningless data overheads Hard for multi-layer cooperation e.g., transit nodes do not know which virtual network, session, or service chain the packet belongs to; hard to achieve fine-grain QoS, security policy. This makes the network to satisfy different requests. Here, the network layer could implement routing/forwarding and policies based on real communicating entities. It would be direct and efficient. Human-based management cannot handle the more and more complex network. Introducing autonomous mechanisms into network could simplify the human management, reduce the human error and the cost of network maintenance, and improve the management efficiency. Introducing AI algorithms may have the chance to unify the solutions for various scenarios.

Another expected issue to be addressed in future networks is massive projected growth of smart IoT devices. These devices will be responsible for sensing measuring and filtering timely response, and they will be interconnected to exchange their collected data to make better observations. Ultimately, IoT devices will open a path for deep discovery and analysis for optimization and forecasting, which leads the network into making smarter decisions and adaptability. However, realizing full potential of smart objects to provides services with heterogenous requirements is dependent on how to handle large-scale communication and computation. For example, computing in a cloud for collected data of IoT objects cannot satisfy low latency requirements. Thus, computation should be performed at end users as much as possible. A new paradigm called edge computing will be essential to enable distributed intelligence in Internet of

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Things, where edge nodes located close to users cooperatively compute and offload the collected data. Only this transition to the network edge architecture can satisfy compelling requirements of services. However. the network processing which is moving toward the edges, needs to simulate/emulate and test the pros/cons of various approaches. One of the foreseen communication approaches is to implement routing and path forwarding between the edge nodes in a distributed and dynamic fashion. This will ensure that services and capabilities can be delivered in minutes or less over managed cloud-native operator infrastructures, which is big step to satisfy latency requirements. Furthermore, by offloading computational function, device battery performance can be increased and likewise life-time of devices can be extended. With the implementation of edge devices, service portals are increasingly located adjacent to users and that means changes to the network: Public Networks no longer carry users' traffic to/from service portals via ISP carriage services. Instead, private Networks carry content to service portals via CDN services. This will open a new network concept called "Content Distribution Network" in which content caches are replicated close to large user populations. Here, the challenge of delivering many replicant service requests over high delay network paths is replaced by the task of updating a set of local caches by the content distribution system and then serving user service requests over the access network. This results in reduced service latency, increased service resilience. In conclusion, moving communication and computation in edge devices can potentially decrease latency and increase the performance of the network. However, due to its large scale and distributed nature, optimized and adaptable (possibly with AI system implementation) architecture will be required for edge computing/communications.

Another aspect to be considered in future networks is security. Security implementations of future networks should be simple but effective such a way that it should not decrease the performance with its high computational needs, which ultimately can increase latency and energy utilization. Thus, the group focuses on analysis of a built-in trustability model that makes users aware of what they are giving up when accessing a particular service. The trustworthy edge-to- edge (E2E) communication is crucial for building a more secure Internet architecture, which provides a reliable secrete key exchange and DDoS defense capabilities while still balancing the tradeoff between accountability and privacy. The existing solutions are fragmented, which mostly patches the partial security issues. In this case, the inherent method is highly required for ensuring the security of E2E communication. The network infrastructure (i.e., BGP and DNS) should be more trustworthy and reliable, which could provide fundamental services for ensuring that the network is working properly in the future. Without relying on a centralized authority, BGP and DNS can inherently immunize against existing attacks (e.g., BGP route leaks and DNS cache poisoning).

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9. TACTILENET CONTRIBUTIONS TO STANDARDIZATION ACTIVITIES

9.1 Activities Reported in Midterm Report

Prof. Gunduz (Fellow ID: 8, ER) from Imperial College London gave an invited talk at the 5G Core Network Summit in Ankara, Turkey on 15.06.2016 attended by over 100 people from the government, academia, and industry. This event was organized by the leading Turkish industry players in wireless communications, HAVELSAN, NETAS and ASELSAN, with the goal of identifying 5G research directions and collaboration opportunities with international partners. Prof. Gunduz presented the 5G-related research activities in his lab, including the collaborative ongoing work carried out within TactileNet. His presentation was an overview of the research activities envisaged by Tactilenet along with his vision of 5G technologies. Henceforth, he promoted the activities of Tactilenet to industry and general public. The website for the information for the summit is https://www.btk.gov.tr/en-US/National-Activity/5G-CORE-NETWORK-SUMMIT-WAS-HELD

Additionally, Prof. Ercetin (Fellow ID: 2, ER) from Sabanci University, joined Networld2020 consortium (https://www.networld2020.eu) as a member representing Sabanci University. Unforeseen at the time of the proposal a new working group has been formed by the IEEE which is the foremost authority in developing standards in communications networks. Prof. Ercetin (Fellow ID: 2, ER) joined the working group of IEEE P1918.1 working group on Tactile Internet: Application Scenarios, Definitions and Terminology, Architecture, Functions, and Technical Assumptions (https://standards.ieee.org/develop/project/1918.1.html). The activities of this standard working group facilitates the rapid realization of the Tactile Internet as a 5G and beyond application, across a range of different user groups. Additionally, this standard working group provides the groundwork upon which the Tactile Internet will be formed. To this end, this standard working group provides a baseline for a pioneering range of further standards that will be created under this working group realizing the key necessary technical capabilities of the Tactile Internet. The activities of this working group started with KO meeting on 27.05.2016. The following meetings were attended by Prof. Ercetin (Fellow ID: 2, ER).

- Online meeting on 27.06.2016 (M5)
- Online meeting on 25.07.2016 (M6)
- Online meeting on 16.09.2016 (M8)
- Online meeting on 13.10.2016 (M9)
- Online meeting on 8.11.2016 (M10)
- Face-to-face meeting 9.12.2016 (during IEEE Globecom2016) (M11).

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- Online meeting on 14.3.2017 (M14)
- Online meeting on 25.5.2017 (M16)

9.2 Activities Performed After Midterm Report

Under WP4, Task 4.1, Prof. Yanikomeroglu (Fellow no.18, ER) gave a tutorial titled "5G and Beyond Wireless Networks: Emerging Concepts and Technologies" during IEEE Globecom 2017 conference in Singapore. The tutorial can be reached at http://www.magnetmail.net/actions/email_web_version.cfm?ep=Qfqs2iYSCyGwCzB5v7o3NjeX8bd4e5VM2GkTbKtjx3eiZpu8fGgTyqmZe5Y4cTj-GBG5i-KzmcNXPJuXGT05GBD6GP4w41tjP84dP-BNyfvldCIfMdCP2xzCCKUmaqOW

Under Task 4.2, Prof. Ercetin (Fellow no 2, ER) and his team continued their participation in IEEE P1918.1 working group on Tactile Internet: Application Scenarios, Definitions and Terminology, Architecture, Functions, and Technical Assumptions (https://standards.ieee.org/develop/project/1918.1.html). The following meetings are attended by A. Farajzadeh (Fellow 22, ESR).

- Online meeting on 10.01.2018 (M24)
- Online meeting on 6.02.2018 (M25)
- Online meeting on 24.05.2018 (M28)
- Online meeting on 19. Jul. 2018 (M30)

Dr. Deniz Gunduz (Fellow no: 8, ER) from Imperial College London participated in the inaugural workshop of the International Telecommunication Union's (ITU) Focus Group on "Machine Learning for Future Networks including 5G" as an invited speaker. The meeting was on 29.01.2018 (M24), in Geneva, Switzerland (https://www.itu.int/en/ITU-T/Workshops-and-Seminars/20180129/Documents/2.%20Deniz%20Gunduz.pdf).

Prof. Ercetin (Fellow no 2, ER) began a collaboration with Turkcell, Turkey on contributing to the activities of ITU Focus Group on "Machine Learning for Future Networks including 5G" in M28.

Dr. Yunus Sarikaya (Fellow no: 35, ER) from Sabanci University participated in ITU Workshop and Focus Group meeting on "Networks in 2030" located in New York, NY, US, from 02 Oct 2018 to 04 Oct 2018 (M33).

Prof. Ozgur Ercetin (Fellow no: 2, ER) participated in Networld2020 General Assembly in Brussels, BE on 15 Nov 2018 (M34) as a full voting member (https://www.networld2020.eu/networld2020-general-assembly-15-november-2018-brussels-2/). Prof. Ercetin participated in ICT 2018: Imagine Digital -

Connect Europe event in Vienna, Austria from 04 Dec 2018 to 06 Dec 2018 (M35). Prof. Ercetin participated in IEEE P1918.1 working group face-to-face meeting collocated with IEEE Globecom 2018 on 11 Dec 2018 (M35) in Abu Dhabi, UAE.

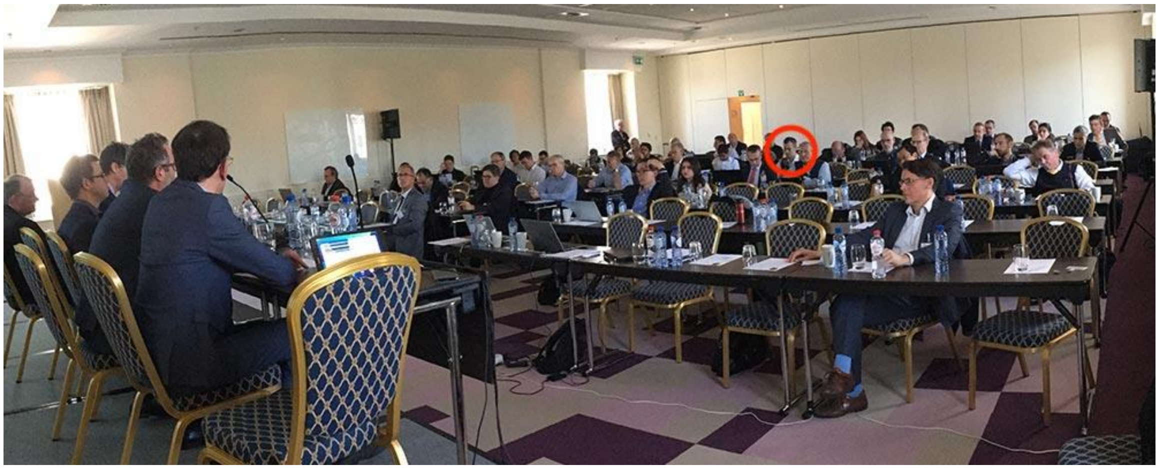

Figure 18. Networld 2020 General Assembly in Brussels. Prof. Ercetin is in red circle.

10. Annex

10.1 List of Industries with which the project outcomes have been disseminated.

Name of the company	Field	Country
Turkcell	Telecommunications Operator	Turkey
Nokia Bell Labs Research Labs	Telecommunications Equipment	Belgium
Huawei Research Labs	Telecommunications Equipment	Canada
Havelsan	Telecommunications Equipment	Turkey
Toshiba Research Lab	Telecommunications Equipment	UK

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