INTERNATIONAL
HELLENIC
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DEPARTMENT OF INFORMATION AND ELECTRONIC ENGINEERING,

MSC IN WEB INTELLIGENCE

Fire-Fighting Drones: A Use Case for Tactile Internet

MASTER'S THESIS
OF
PAVLOS KOSTOULAS

Supervisor: Periklis Chatzimisios
Professor, International Hellenic University

Thessaloniki, September 2021

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Thessaloniki, September 2021

(Signature)

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Pavlos Kostoulas
BSc Computer Science, Hellenic Open University

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Περίληψη

Τίποτα δεν προμήνυε ότι η κατασκευή μίας υποτυπώδους ιστοσελίδας στο κλειστό δίκτυο του CERN το 1990, θα έφερνε την επανάσταση που βιώνουμε καθημερινά στα στον παγκόσμιο ιστό και στις ασύρματες επικοινωνίες. Πράγματι, οι αυξημένες δυνατότητες που προσφέρουν οι πολύ υψηλοί ρυθμοί μετάδοσης και η διευκόλυνση της μετάδοσης της πληροφορίας που έχουν φέρει τα κυψελωτά δίκτυα, καθιστούν δυνατή τη μετάβαση στο επόμενο στάδιο, που είναι η μετάδοση και η λήψη της απτικής πληροφορίας. Το Απτό Διαδίκτυο, είναι το μέσω το οποίο θα επιτρέπει τη μετάδοση και λήψη των απτικών πληροφοριών σχεδόν σε πραγματικό χρόνο, αξιόπιστα και με ασφαλή τρόπο. Το μέσο που θα βοηθήσει στην υλοποίηση του απτού διαδικτύου, είναι η ραγδαία εξέλιξη των ασύρματων δικτύων γενικότερα και η ανάπτυξη των ασύρματων δικτύων 5ης γενιάς.

Στην εργασία παρουσιάζονται τα βασικότερα ζητήματα σχετικά με το Απτό Διαδίκτυο. Περιγράφονται οι σημαντικότερες ερευνητικές προκλήσεις, οι τομείς της καθημερινής ζωής όπου θα εφαρμοσθεί και οι τεχνολογίες που θα στηρίξουν την δημιουργία των μελλοντικών δικτύων. Η ανάπτυξη του πρώτου προτύπου για το Απτό Διαδίκτυο από την ομάδα εργασίας της IEEE αποτέλεσε σημαντικό βήμα.

Επιπλέον, δίνεται ένα παράδειγμα του τρόπου με τον οποίο ένα συγκεκριμένο σενάριο του Απτού Διαδικτύου – η δασοπυρόσβεση με μη επανδρωμένο εναέριο όχημα - μπορεί να εφαρμοστεί προτείνοντας μια μηχανή πεπερασμένης κατάστασης. Τέλος, υλοποιήσαμε παραδείγματα ανταλλαγής μηνυμάτων και μετάβασης (ASN.1), βασιζόμενοι στο πρότυπο του IEEE P1918.1.

Λέξεις Κλειδιά: Απτό Διαδίκτυο, Τεχνολογίες 5ης Γενιάς, Χαμηλή Καθυστέρηση, Υψηλή Αξιοπιστία, Ασφάλεια, Προτυποποίηση

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Abstract

Nothing could have predicted that the construction of a rudimentary website on CERN's private network in 1990 would bring the revolution we are experiencing every day in web and wireless communications. Indeed, the increased possibilities offered by the very high transmission rates and the facilitation of information transmission brought about by cellular networks make it possible to move to the next stage, which is the transmission and reception of tactile data. The Tactile Internet is the medium that will allow the transmission and reception of haptic information in almost real-time, reliably, and securely. The medium that will help in the implementation of the Tactile Internet, is the rapid development of wireless networks in general and the development of 5th generation wireless networks in particular.

The paper presents the key issues related to the Tactile Internet. It describes the main research challenges, the areas of everyday life where it will be applied, and the technologies that will underpin the creation of future networks. The development of the first standard for TI by the IEEE working group was an important step.

We also give an example of how a specific scenario of the Tactile Internet - wildfires firefighting with an unmanned aerial vehicle - can be implemented by proposing a finite state machine. Finally, we implemented examples of message exchange and transition (ASN.1) based on the IEEE P1918.1 standard.

Keywords: Tactile Internet, 5G, Internet of Skills, SDN, NFV, Latency, firefighting drones.

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Acronyms

A – Actuator
AI - Artificial Intelligence
AMR - Anisotropic Magneto Resistive
AN - Actuator Nodes
BS - Base Station
CN - Controller Node
CPE - Control-Plane Entity
DoF - Degrees of Freedom
DoS - Denial-of-Service
E2E - End-to-End
eMBB - Enhanced Mobile Broadband
GN - Gateway Node
GNC - Gateway Node Network Controller
HIS - Human-System Interface
HN - Human System Interface Node
HRR - Heat Release Rate
IMUs - Inertial Measurement Units
IoD - Internet of Drones
ITU - International Telecommunications Union
KPIs - Key Performance Indicators
MEC - Multi-access Edge Computing
MIMO - massive Multiple Input Multiple Output
mMTC - Massive Machine-Type Communications
mmWave - Millimeter-Wave
NC - Network Controller
NFV - Network Function Virtualization
PGW - Packet Gateway
QoE - Quality of Experience
RAT - Radio Access Technology
S - Sensor
SAR - Search and Rescue

SDN - Software Defined Networking

SE - Support Engine

SGW - Serving Gateway

SN - Sensor Nodes
TD - Tactile Device

TI - Tactile Internet

TSM - Tactile Service Manager

UE - User Equipment

UAS - Unmanned Aerial System

UAVs - Unmanned Aerial Vehicles

UPE - User-Plane Entity

URLLC - Ultra-Reliable and Low Latency Communications

VR - Virtual Reality

WG - Working Group

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Introduction

It has been more than thirty years ago (in the 1990s) when Sir Timothy John Berners-Lee shocked the scientific community and the whole world by publishing the first website, in the CERN's network [1]. Since then nowadays, the Internet became faster, more reliable, more securable.

Additionally, mobile networks gave more capabilities with the ability to have fast, reliable, and safe internet almost everywhere. But which will be the next step in our network "journey"?

The answer is Tactile Internet (TI) which will allow us to transmit and receive haptic data in almost real-time, reliable, and secure, that revolutionize various applications like Internet of drones, education, mobility and traffic, health care, sports, entertainment, gaming, and the smart grid, etc. Obviously, TI will dramatically reshape our society.

1.1 The definition of Tactile Internet

The first definition of TI was given by the International Telecommunications Union (ITU) in 2014, as follows [2]:

"Internet network combining low latency, a very short transfer, a high availability and high reliability with a high level of security".

Subsequently, the IEEE 1918.1 Working Group (WG) in 2019 in [3] defined TI as follows:

"A network (or network of networks) for remotely accessing, perceiving, manipulating, or controlling real or virtual objects or processes in perceived real-time by humans or machines"

Building on the above-mentioned definition, WG detail seven core aspects of TI as basic assumptions.

- TI gives the opportunity, for remote physical interaction, by exchanging haptic information.
- This interaction is bidirectional and may be among humans or machines or the opposite.
- As "objects", physical entities are meant (including humans). The term Machines refers to robots and generally connected entities.
- Scenarios encompassing human-in-the-loop physical interaction with haptic feedback are often referred to as bilateral haptic teleoperation. The goal of TI in such scenarios

is that humans should not be able to distinguish between locally executing a manipulative task compared to remotely performing the same task across TI.

- The results of machine-in-the-loop physical interactions will ideally be the same as if the machines were interacting with objects directly at or close-to-the locations of those objects.
- There are two categories of haptic information, namely, tactile or kinesthetic, or a combination of them. Tactile information refers to the perception of information by the various mechanoreceptors of the human skin, such as surface texture, friction, and temperature. Kinesthetic information refers to the information perceived by the skeleton, muscles, and tendons of the human body, such as force, torque, position, and velocity.
- Use case specifications will define the perception of “real-time” for users.

1.2 The 5G in TI services

From the definition that is quoted in the previous subchapter, we can assume that to make the vision of TI a reality, a whole new network ecosystem is required, in order to meet the requirements of the new, demanding network (TI). Thankfully the latest year a new generation of mobile network appeared the 5G and although the pure coverage, in some years 5G will dominate the mobile networks and will provide all the necessary provisions in order to give us haptic communications with the minimum latency, the maximum reliability and as secure as possible. In order to realize the evolution that 5G networks brought to our life, we will give the historical background of mobile networks (Figure 1):

- The 1st generation was announced in the 1980s. It offered analog transmission of voice, using Frequency Division Multiple Access as a channel access method. The voice quality was poor, so the battery life of the devices and the maximum speed of 1G was 2.4 Kbps.
- The 2nd generation utilized digital signals for voice transmission. This generation provided services like SMS, MMS. For the first time, the data encryption method has been used.
- The 3rd generation of mobile services systems offered higher speeds to services based on Internet Protocol (IP). The 3G introduced services offered by mobile Internet. The data rates ranged from 144 kbps to 2 Mbps. By using smartphones the user could have rapid transmissions, they could send emails, faster web browsing, and video streaming was introduced [4].

- The 4rth generation of cellular networks integrated services such as download or browse demanded faster and efficient data transfer networks. It also offers Video Conferencing, HD mobile TV, gaming services that require an ultra-fast network. The fourth-generation (4G) data rates range from 100 Mbps to 1 Gbps [5].
- The 5th generation by using advanced access technology named Beam Division Multiple Access and Non- and quasi-orthogonal or Filter Bank multi-carrier multiple access. So the 5G is expected to provide data rates up to 50 Gbps and reliable connections by using Low-Density Parity-Check Codes.

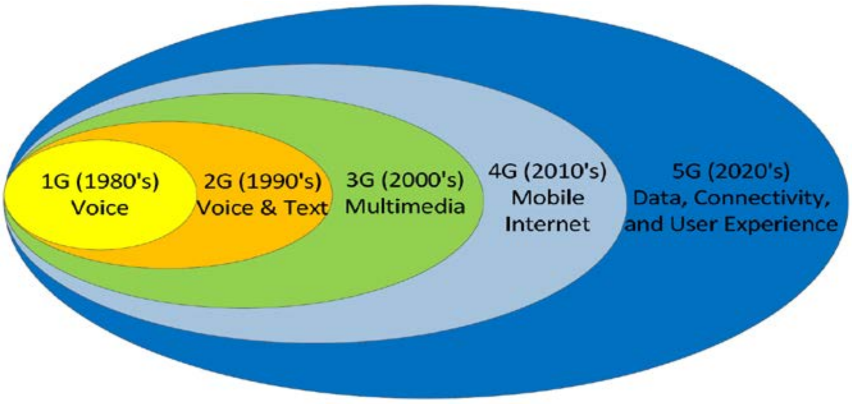

Figure 1 Development of service types over wireless mobile generations [6]

1.3 Purpose and Structure of the Thesis

This thesis aims to summarize the prominent technology notions which are met at TI and the features that 5G networks are needed. It will expand many application fields and make possible a large set of use cases. These use cases will, in particular, change drastically the whole society. We describe the applications, in which TI will play a cardinal role in our society. Moreover, we emphasize the drone domains and specifically firefighting drones, and how TI will aid efficiently to the wildfires extinguish.

This Thesis is organized as follows. Chapter 2 Background and motivation, has two main subchapters. The first describes TI applications, TI requirements and features, TI challenges, the way the 5G ecosystem will enable TI vision, and the basic 5G technologies that will aid the implementation of TI systems. The second is dedicated to unmanned aerial vehicles (UAVs) or drones. Initially, we attempt to provide general information about drones and how they can be used in disasters and in particular the usage of firefighting drones. In Chapter 3 Firefighting Drones over TI, we attempt to provide the main components of TI architecture and how is implemented in TI considering the IEEE P1918.1 Standard reference architecture. In Chapter 4 Use case and implementation, a completely new attempt is made. The way a TI scenario – The

Firefighting Drones – can be enhanced with the implementation of TI is illustrated. Finally, some instances of TI in a firefighting drone are described with examples of messages exchanged (in the form of ASN.1 messages) and state transitions. In Chapter 5 Conclusions & Future work, basic conclusions are highlighted and future work directions are described.

2

Background and motivation

2.1 The Tactile Internet

In this section, we will summarize the basic aspects of 5G technology and TI and how they will cooperate to make real TI vision.

2.1.1 Tactile Internet Applications

In this section, we will summarize some of TI applications, which will play a major role almost in every aspect of society (Figure 2).

2.1.1.1 Healthcare

In the healthcare, domain are opened new sectors in almost every aspect of medical science. In particular diagnosis by distance, telesurgery, medical education by distance and telerecovery, are just some of the domains that could be benefited from TI. For the implementation of those use cases, without any serious issues that could even drive to human lives being lost, it's necessary to the precise, stable, reliable, and with minimum loss data transmission. Moreover, besides the multimedia data, it's vital to receive also haptic data with only 1ms overall latency, according to the use case. Also, the use of exoskeletons for the cure and support of people with disabilities is a use case in that TI could play a cardinal role to provide distance help by the therapist [8], [9], [10], [11], [12], [13], [14], [15].

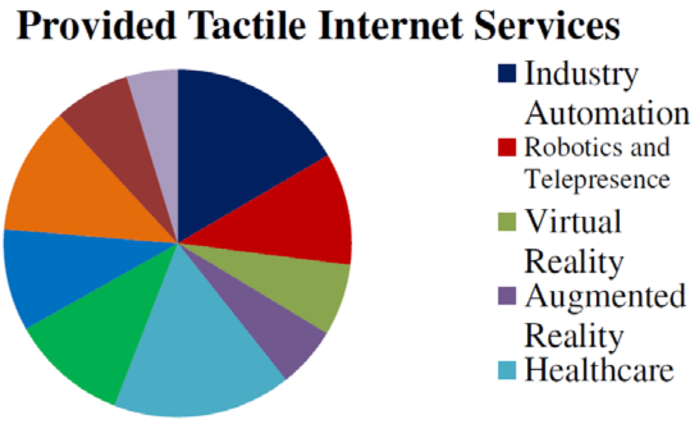

Figure 2 TI Applications [7]

2.1.1.2 Industry And Robotics

TI will bring dramatic changes to the industry. The lines of production will use robots and they will communicate directly with latency up to 1 ms which in particular means immediate communication. They could remain inert until the moment they will need to gain low energy consumption. They will be able to cooperate, autonomously and they will exchange immediate data. The smart industries will have a flexible line of products and will produce personalized products, being always adopted directly to market requirements [11], [9], [15]. It will be possible to control devices that move quickly and to make complex objects from the security and comfort of the office [11], [16]. The robots will be cooperative, autonomous, self-governing, and intelligent learning. Alternatively, there will be remote-controlled robots [8], [10], [15].

2.1.1.3 Smart Grids

Efficient, reliable transmission and distribution is the basis for a secure energy supply. The stability of the supply requires synchronization [9] and intelligent networks are developed that will not have fluctuations in volts. Education will benefit immediately with a large reduction in operating costs and money will be channeled directly to education. With the saying of smart meters and intelligent recording, accuracy in measurements is achieved. They turn suppliers on and off to achieve stability. To achieve this, a delay of <1 ms is required here as well [8], [9], [12].

2.1.1.4 Serious Gaming

Electronic learning games are made for special purposes by solving problems with several applications such as education, training, simulation, and health, e.g., with exercise games (exertion games). The end-to-end (E2E) delay of a few ms and the use of sensors and actuators will open new doors for direct interaction, player experience, and tactile collaboration, [15]. The main goal that should be achieved is the simultaneous sense of the game that all the players must feel, otherwise we will be led to injustices [12], [16].

2.1.1.5 On-line Shopping - Training – Business

Before buying a product, the buyer could touch the texture of a product or even try it virtually to see if it suits him/her. Tactile contact will generally affect all e-commerce and education as teachers will be able to feel the material they want to order. TI is geared towards applications that will offer many business opportunities including users, providers, and sellers by integrating different business sectors (transport, oil companies) [16], [15].

2.1.1.6 *Internet of Drones*

UAVs or drones are currently, are used in a wide range of applications. UAVs at their early stages were used in military applications, however, nowadays drones are used by kids as toys, from photographers as aerials cameras, from rescuers for search and rescue (SAR), from doctors for delivering sensitive biological material for medical exams without being stuck in traffic jams [17], from merchants for e-commerce even from firefighters to detect earlier a wildfire. Drones are aerial platforms that can carry out a variety of sensors to detect smoke, chemicals, radioactivity, cameras [18] even thermal cameras are being installed for SAR operations [19]. Drones can be used for mapping and monitoring [20] disaster areas where the terrain isn't accessible, or dangerous for the personnel [21]. The population of drones that have been manufactured is rapidly increased, we have to mention that according to [22] the market of drones had absorbed almost one hundred billion dollars from 2016 up to 2020. The IEEE P1918.1 WG has indicated the transmission requirements of the Internet of Drones (IoD) over TI based on whether haptic information is involved (Table 1). There are 3 different scenarios, IoD without haptic information involved, IoD with haptic information involved and humans acting as manipulators, and IoD with haptic information involved where a machine is acting as manipulators. Based on TI, the IoD will be able to provide fast, reliable, and safe services to critical applications [3], [23].

Table 1 KPI Requirements and Traffic Characteristics for TI for IoD Use Case based on [3]

Use case / scenario	**Traffic direction**	**Traffic types**	**Burst size**	**Reliability (%)**	**Latency (ms)**	**Average data rate**
Internet of Drones (with humans; without human latency requirement 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.)

2.1.1.7 Edutainment - Training – Practice

The training could be transacted in multiple ways, the goal is to make training more attractive by implementing sound, vision, and touch, where the instructor could intervene immediately and by distance to correct the trainee.

For instance, a piano teacher who wants to teach a student how to play the piano (Figure 3) [24], or a medical student that makes his first surgery. Furthermore, an orchestra which plays without being present all its members. Additionally, TI could guide hands and fingers by using gloves by giving trainees creative abilities. Moreover, students with special abilities (e.g. blind, autistics) could have training courses based on touch and object recognition, like shapes and surfaces.

2.1.1.8 Virtual Reality

In a haptic virtual reality (VR) environment, users could work together, through a simulation tool, to perform tasks, in case they do not perceive and control the objects not only visually but also with the sense of touch. [8], [9], [15]. If they interact with the same object, they could feel each other's movements or actions. [8], [9], [15]. The user movements will be transferred to TI server, where the simulation is calculated, and the result will be returned to the users as updated information about the status of the object along with tactile feedback. [8], [9]. Today's TI systems suffer from long enough communication delays and require stability and constant coordination so that users have a consistent view of the virtual environment locally. [9], [15]. Wired communications may not be sufficient for remote users [9]. TI will be an integral part of training in many subjects, with the first steps becoming a reality with TI applications (Figure 4).

Figure 3 Tactile Teacher Prototype with a microcontroller (left) directly connected to an instrumented glove (right) [24]

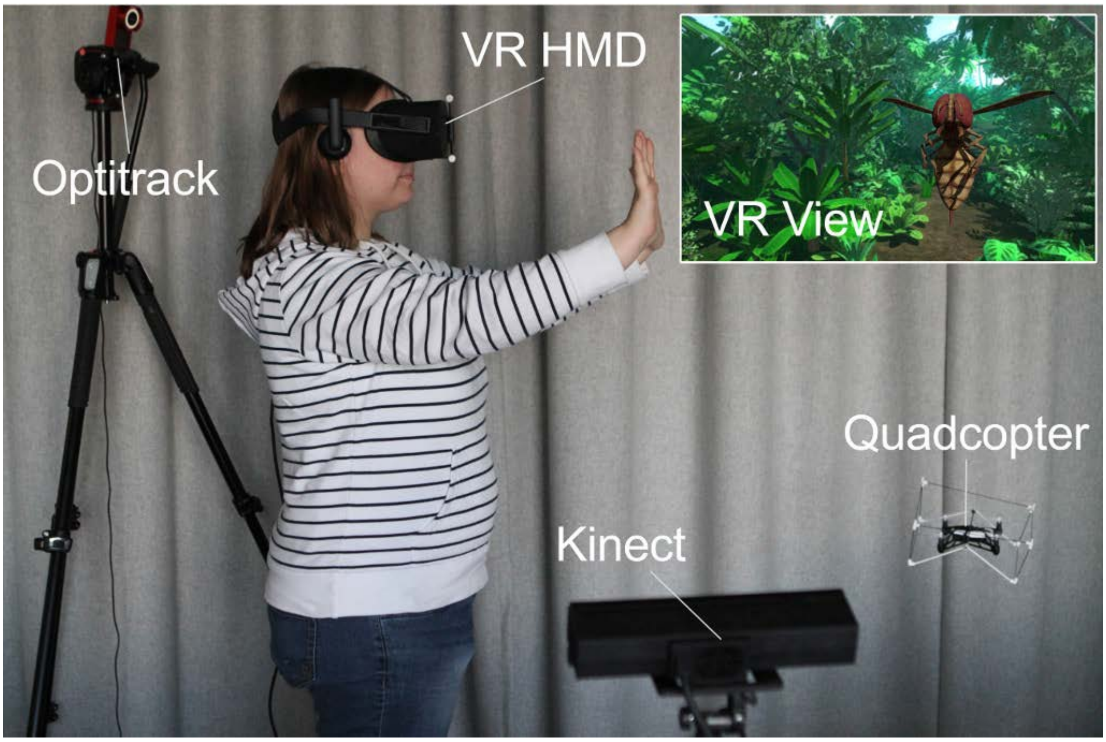

Figure 4 User immersed in virtual reality Tactile Drone system. While tactile feedback is generated by a quadcopter, it is perceived as a hit from a bumblebee [20]

2.1.1.9 Augmented Reality

Augmented Reality (AR) applications are favored and experiencing tremendous growth due to the easy access to VR glasses, smartphones, and tablets, which contain cameras and sensors [9]; [15]. In VR, where a combination of real and virtual content is presented to the user's field of vision, the greatest goal of future applications, compared to augmenting only static information today, is to visualize dynamic content as well as real-time updated information [11]. TI can overcome these obstacles and allow the development of many new assistance systems, such as driving (identification, risk avoidance), training, touring cities or museums, and the work of police and firefighters [11]; [9]. For instance, in driving, potential hazards or obstacles can be detected by other vehicles, which will transmit this information in real-time to the following vehicles [9].

2.1.1.10 Autonomous Driving

Autonomous vehicles with partial or fully automatic driving will radically change the driving experience and bring benefits to society and the economy (Figure 5). In partially automatic driving some features, such as automatic parking, cruise control, or emergency braking, are already a reality. [9], [11], [15]. Fully automatic driving, combined with real-time communication-tuning and improved safety, could make it unnecessary for traffic lights and vehicles to cross intersections without colliding [9]. There will also be time savings. [9], [11]. In the case of platooning [9], a formation series of vehicles at a constant speed one behind the other at close distances from each other, coordination between vehicles is required, which imposes a response time of 1-2 ms [11]. Other applications include the detection of moving objects (eg pedestrians) by radar or cameras and the transmission of information to neighboring vehicles [9]. Moreover, remote driving could contribute also to distance education.

2.1.1.11 Free-Viewpoint Video

Video from different angles is the result of the synthesis of video information resulting from digital image processing to render the viewer-observer the view from a different point of view. In the future, we will have the option of dynamically changing this perspective. An interesting example would be watching television (e.g., school) games, educational events and speeches, music events, and other events in stadiums or venues with hundreds of cameras. But for real-time rendering of the angle of view, the delay should be minimized [9]. Similar applications would be between cars on the road, between vehicles in logistic hubs as well as between pedestrians in crowded areas.

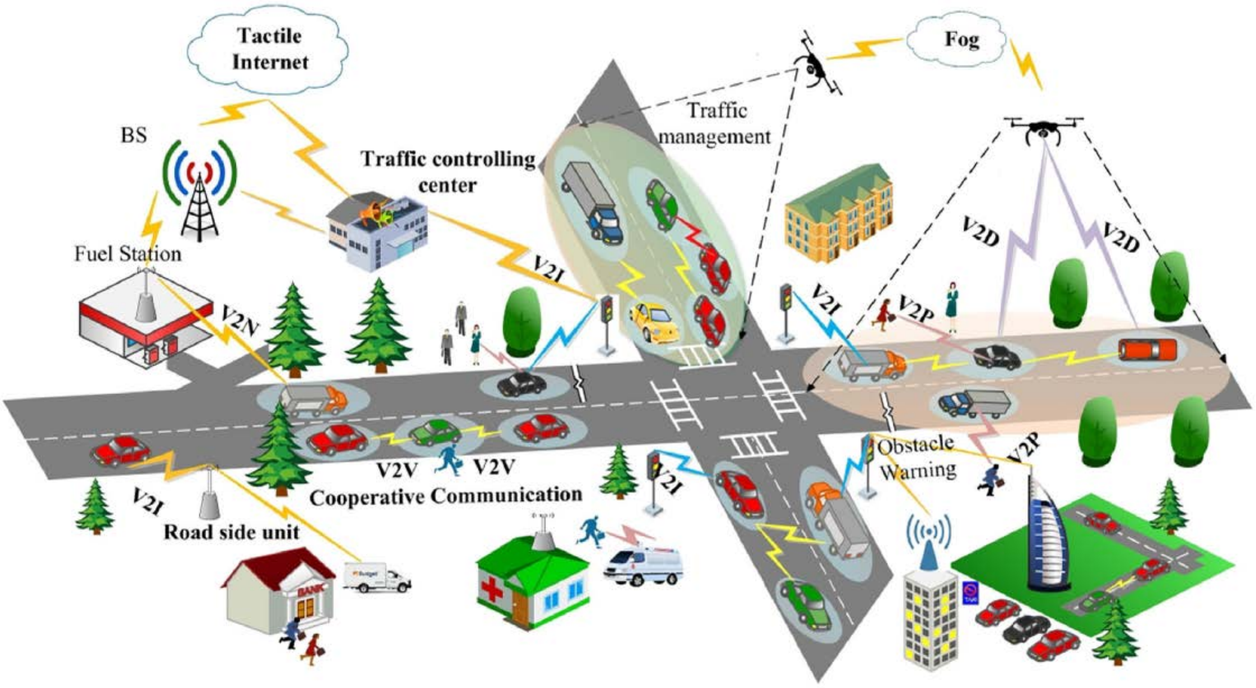

Figure 5 5G-enabled TI-based architecture for autonomous cars [13]

2.1.2 *Tactile Internet Requirements-Features*

In TI, operators could handle appliances by distance and at the same time should receive and transmit haptic feedback. TI has to overcome design challenges that have many similarities to IoT challenges. It is also, very important to overcome, the issue of different reaction times up to 1 millisecond that is required by humans to interact using audio, video, and haptic interaction. The main aim of TI is to have a human touch over the communication network Figure 6. The key requirements for realizing TI are as follows:

- Ultra-responsive connection: TI requires ultra-low E2E latency, ie, less than 1 millisecond for real-time data or touch transmission, depending on the application. For instance, applications like health care or autonomous cars require a latency of up to 1 ms, other applications that aren't mission-critical like surveillance drones or online shopping have less strict limits.
- Ultra-reliability: TI requires availability near 100%, is expected to serve sensitive applications such as health care, and transportation that requires ultra-high reliable connectivity of 99.99999% which reduces the system outage probability to 10^{-7} or 3.17 seconds per year.
- Security and privacy: TI requires the implementation of new coding techniques to forward a message only to the authorized receiver. Proper identification of authorized users in fully connected applications is the main challenge.
- Tactile data: TI requires management of the tactile information along with audio/visual data also.

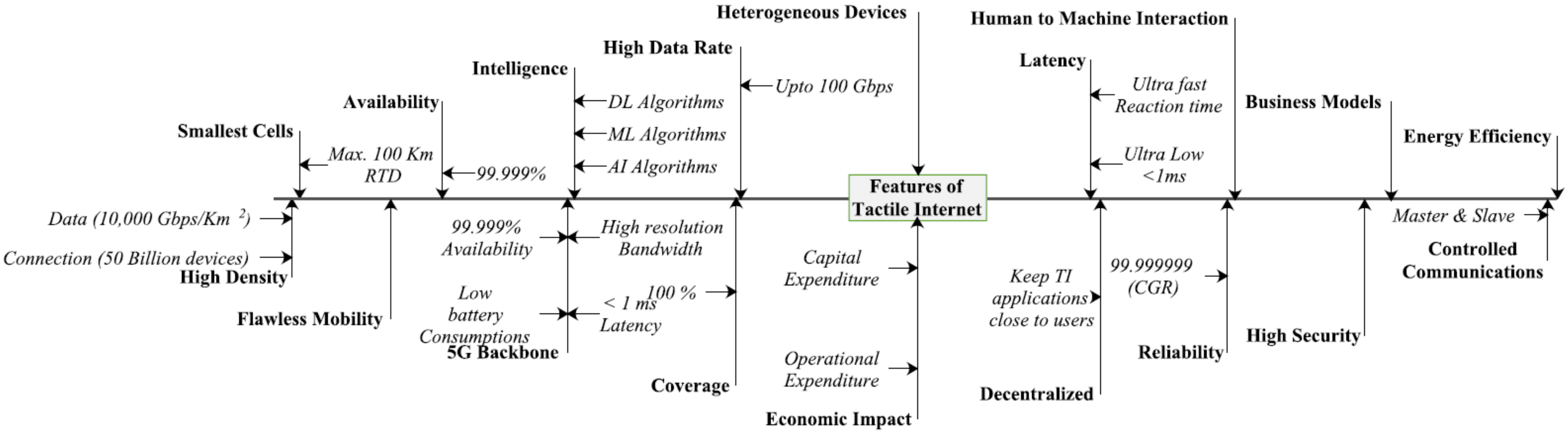

Figure 6 Features of TI [13]

2.1.3 Tactile Internet Challenges

In this section, we outline some of the key research challenges and open problems in realizing TI.

2.1.3.1 1 ms Latency

Latency is a requirement that is basic in various TI applications, especially mission-critical applications that require strict limits, of E2E latency up to 1 ms.

By E2E latency we mean the duration it takes for the transmission of a packet from the source (master domain) to a recipient (slave domain), including the confirmation that returns to the transmitter that the packet has been received. Furthermore, the date packet will visit a specific number of network elements, which influence the E2E latency. Apparently, to achieve the goal of 1 ms latency, the number of network elements should be reduced [25].

To achieve, a lifecycle of 1 ms latency, a methodology should be followed, from the first stage where the data is produced from a sensor to decisions making during a TI transmission. The apportionment of the latency of 1ms is illustrated in Figure 7 and is clarified as follows:

- 0.4 ms are apportioned to sensors, actuators, and generally the embedded techniques in the two edges. As depicted in Figure 7, 0.1 ms could be apportioned to the sensor and the system that evaluates the data, 0.1 ms to network latency, and 0.1 ms for the corresponding procedure at the actuator’s side.
- 0.6 ms are apportioned to the network domain. The network domain contains components that play a vital role in the delay, it usually contains devices such as switches and routers. The above-mentioned components have the ability to manage the data they receive. To achieve the goal of 0.6 ms for the network domain the implementation of new technologies like Software Defined Networking (SDN) and Network Function Virtualization (NFV) are necessary. SDN and NFV processed in Multi-access Edge Computing (MEC) cloud systems have been proposed as critical paradigms for achieving the low latency requirements of TI. In particular, MEC will enable the reduction of communication latency because the management of data occurs near the user. For instance, for a distance of 25 km between the edges and the MEC, the round-trip could consume 0.25 ms and 0.35 ms could be consumed for NFV (Figure 7) [26].

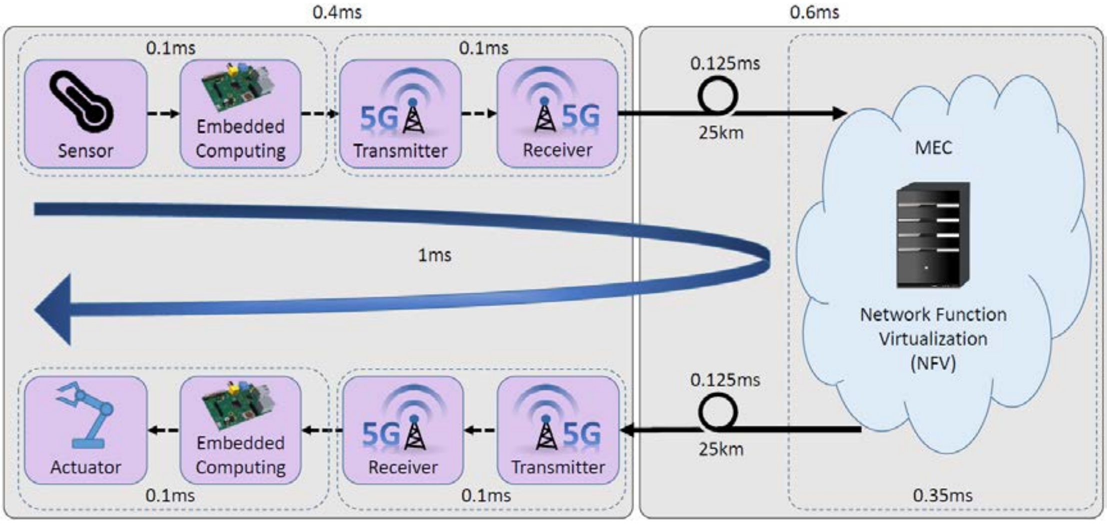

Figure 7 Typical latency budget for sensor-to-actuator control loop that meets one-millisecond round-trip latency [26]

A typical issue that is created is the latencies that affect the overall latency. To meet the requirement of 1ms, those latencies should be reduced. Moreover, innovative and efficient methods like improvements in the mobile network, core network, core Internet are necessary, for the 1ms challenge to become reality, keeping always in mind the speed light which is the main barrier [10].

The efficiency of a use case is highly affected by lags that are larger than the 1 ms in a TI system. Those lags could cause, cyber-sickness that appears to the user. Cyber-sickness is an effect that especially in applications like healthcare has serious circumstances that could be even the death of the patient. The maximum distance the light can travel in 1ms is almost 300Km (because of the light speed 299 792 458 m/s). The two edges of a TI service must be in distance up to 150Km [3], because of the feedback that should also be transmitted and received. Unfortunately, in a tactile system, this distance isn’t acceptable. Subsequently, the distance could be increased (emulsion) by sacrificing the user’s Quality of Experience (QoE) [25], [27].

2.1.3.2 Ultra-High Reliability

Another challenge that plays a cardinal role to achieve the vision of TI, is the ultra-reliable network connection. By ultra-reliable, we mean the network that could provide a service with a percentage that tends to 100%. Apparently, because of the significance that TI applications will play in society and humans’ daily life, the ultra-reliable network is a necessity. Unfortunately, existing networks, are vulnerable to various factors such as uncontrollable interference, decreased power of the useful signal, resource depletion, equipment failure, etc. Moreover, ultra-reliable can be quantified in terms of fixed-line carrier-grade reliability of seven nines, i.e. an outage probability of 10^{-7}, which refers to milliseconds of outage per day. Ultra-reliable network connectivity is critical in keeping packet losses to a minimum. Moreover, it is observed that networks that tend to lose packets, produce haptic communications that are exposed to different types of artifacts, with the main effect the undesirable strong forces and surface roughness [10]. For being sure that haptic, audio and visual data will be transmitted efficiently the system should be reliable with a maximum packet loss probability of 0:001%, otherwise there is a high possibility QoE, of the user to be affected [27].

2.1.3.3 Security

As it is easily understood security is one of the hardest challenges of TI. Our recent experience has shown us that TI networks should cope with various threats such as denial-of-service (DoS), eavesdropping, man-in-the-middle, etc. but at the same time should keep the E2E latency up to 1ms.

The impact that TI will have on society makes the need for secure networks urgent. For sure we don’t want to imagine the consequences of a DoS attack on a hospital network the time that a serious surgery is taking place, or when a large UAV is flying over a big city. Additionally, we should consider the security challenge, following the 1ms latency, requirement. The security requirement in a TI system isn’t limited to access to data by unauthorized individuals but is also an issue of trying to keep E2E latency at acceptable levels.

Subsequently, the application plays a major role in the selection of the desired security measurements against E2E latency. For instance, in health care applications, we strongly care about both security and E2E latency, it is easily understood that we don’t want the cyber sickness effect but at the same time we don’t want also, unauthorized users in our system. On the other hand, in VR applications, we also require a low E2E delay but with a lower requirement for the secrecy of the haptic information. So, the required security level should be traded-off with the increase in delay, which will lead to different security levels across the wide range of haptic applications [27], [2].

2.1.3.4 Haptic Devices

Haptic devices play a vital role in enabling haptics, by allowing the operator to receive and transmit touch, feel, and operate objects. Moreover, haptic devices are now widespread even for commercial uses, e.g. devices with up to 6 degrees of freedom (DoF). For instance, a popular design for haptic devices is a linkage-based system that consists of a robotic arm attached to a stylus (Figure 8). The robotic arm follows the position of the stylus and can press the same force on the tip.

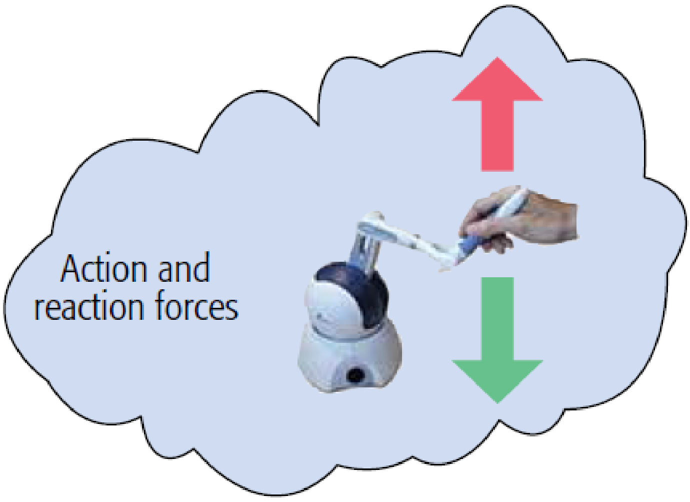

Figure 8 Example of a haptic device [10]

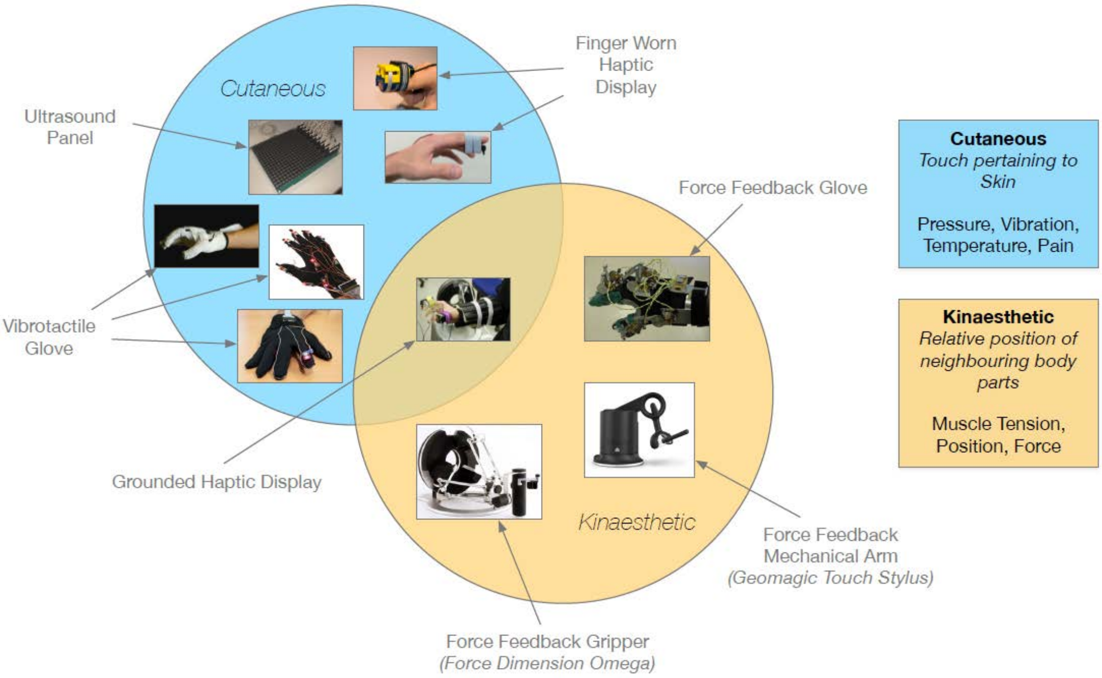

Figure 9 An overview of haptic feedback devices [27]

For TI to become a reality, more efficient (increased DoF), with lower costs and with the ability to serve all the possible applications haptic devices must be developed. Also, the development of devices with the ability to provide both kinesthetic control and tactile feedback is a need, because most devices offer kinesthetic control only one ability (Figure 9).

2.1.3.5 Haptic Codecs

One of the major challenges in realizing TI is the implementation of codecs for kinesthetic and tactile information exchange across communication networks. The capturing of visual and auditory information is predominant in modern multimedia systems. On the other hand, the integration of visual, auditory information and at the same time the transmission of haptic information, by the development of a standard haptic codecs family. is one of the main challenges of TI (P1918.1.1).

Subsequently, the development of standard haptic codecs, similar to video (H.265/HEVC) codecs is a necessity. Unfortunately, technical solutions addressing the sense of touch, in contrast, have not yet reached the same level of sophistication. Haptic information needs to be captured, compressed, transmitted and displayed with minimum latency. The compression of haptic information is handled by haptic codecs [28], [10].

2.1.4 Tactile Internet and 5G

In this section, we will outline the key characteristics of 5G and the reasons that make it necessary for enabling TI. As shown in Figure 10, 5G will continue the successful course of 4G and will not only provide human communication but also fulfill the communication requirements of the vertical communities, e.g., industrial, agricultural, medical, traffic, financial, and environment.

2.1.4.1 key Performance Requirements of 5G

The key performance requirements for 5G are derived for each scenario according to the predicted distribution of users, percentage of different services, and service requirements, such as data rate and latency, which play a cardinal role in TI distribution. 5G systems must dramatically outperform previous generations and 5G should provide the following characteristics:

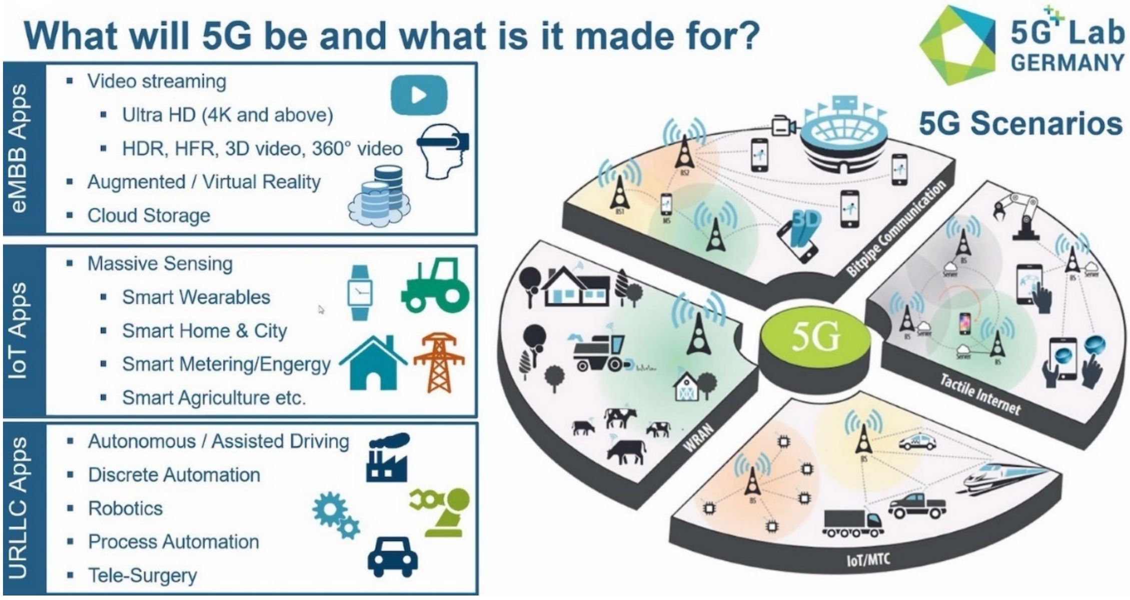

Figure 10 General vision of a 5G system [29]

- User-experienced data rate: 0.1–1 Gbps
- Connection density: 1 million connections per square kilometer
- E2E latency: millisecond level
- Traffic volume density: tens of terabytes per second per square kilometer
- Mobility: higher than 500 Km/hour
- Peak data rate: tens of Gbps

Among these requirements, user-experienced data rate, connection density, and E2E latency are the three most fundamental features of 5G. The performance and efficiency requirements of the technology jointly define the key capabilities of 5G, which are illustrated in Figure 11.

2.1.4.2 5G Network Services

According to ITU, 5G network services comprise three categories depending on applications include [31], [32]:

- Enhanced Mobile Broadband (eMBB), which addresses the human-centric use cases for access to multimedia content, services, and data (e.g., 3D video, UHD (Ultra-High Definition) screens, AR, etc.).

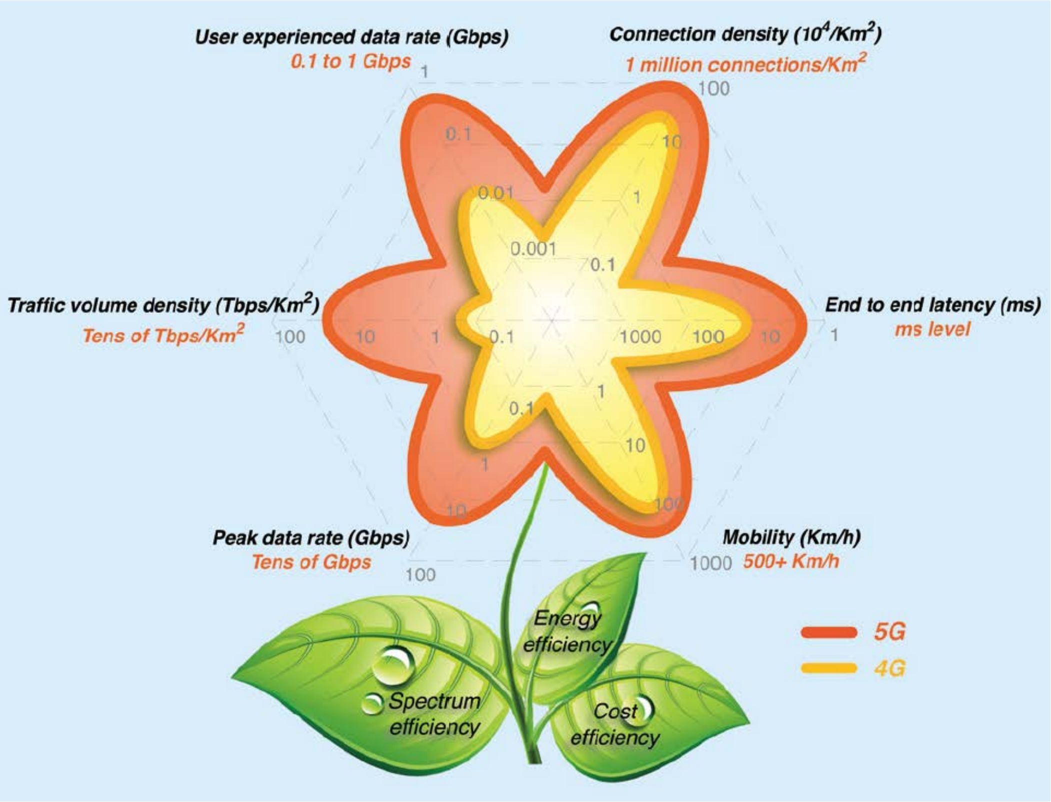

Figure 11 Key capabilities of 5G [30]

- Ultra-Reliable and Low Latency Communications (URLLC), which has stringent requirements for capabilities such as throughput, latency, and availability (e.g., industry automation, mission-critical applications, self-driving cars, etc.).
- Massive Machine-Type Communications (mMTC), for scenarios with a very large number of connected devices typically transmitting a relatively low volume of non-delay sensitive data (e.g., smart grid, smart home/building, smart cities, etc.).

The above-mentioned services in accordance with the required applications and the network services in different usage scenarios are depicted in Figure 12 and Figure 13 (i.e., eMBB requires a high data rate, whereas mMTC needs high connection density for massive deployment and, URLLC demands ultra-low latency).

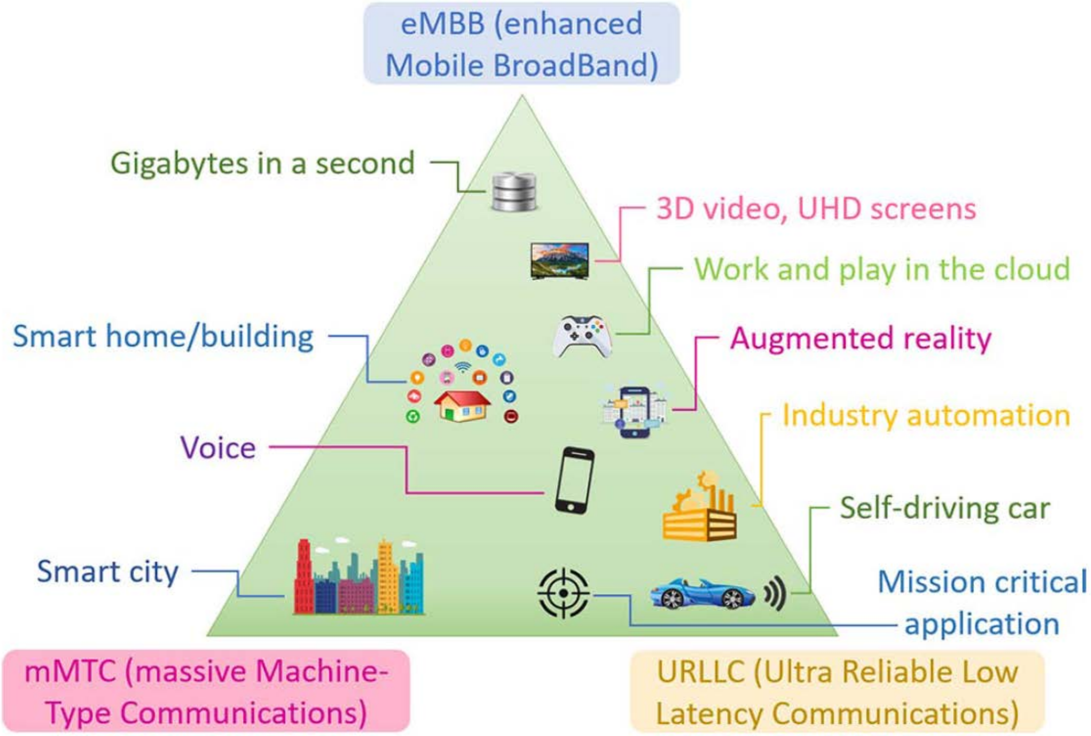

Figure 12 Usage scenarios in accordance 5G network services [32]

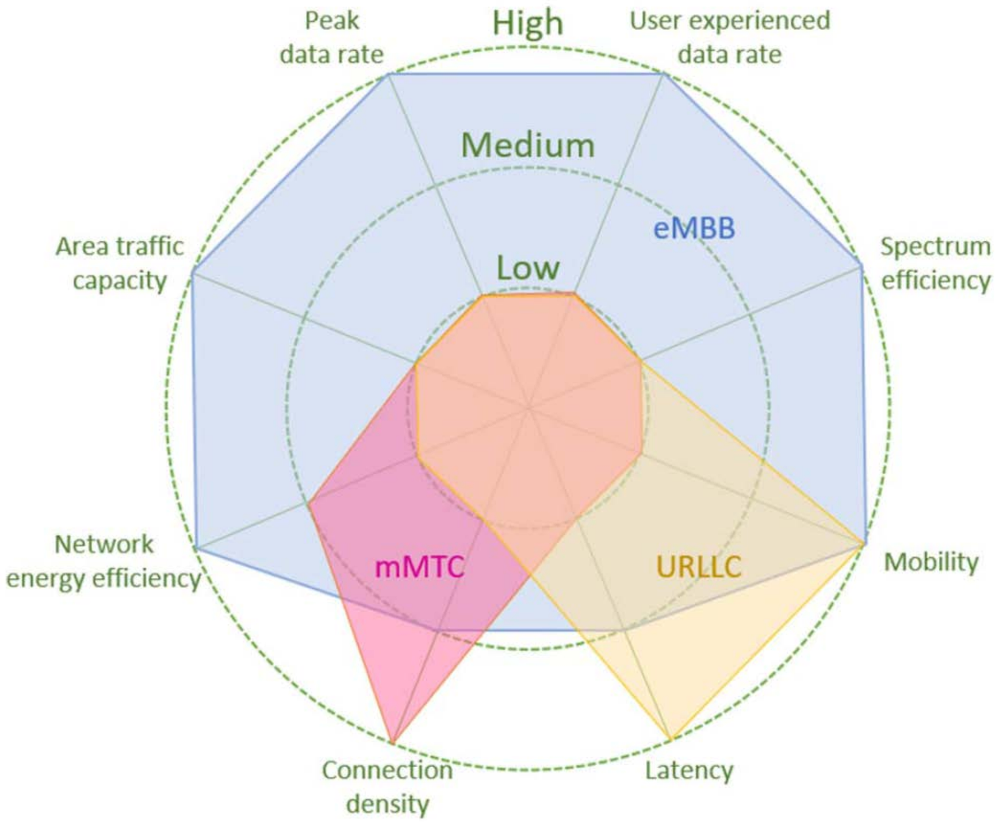

Figure 13 The importance of key capabilities in different usage scenarios [32]

2.1.5 5G Technologies

To meet the requirements, of 5G, technological trends should be defined. Therefore, 5G technologies that are responsible to deliver a more efficient usage of spectrum and an increased output, are the following:

- Ultra-densification
- massive Multiple Input Multiple Output (MIMO)
- Millimeter-wave (mmWave).

Generally, because of the impact that 5G will have on society, it is crucial a reliable coverage.

2.1.5.1 Massive MIMO (Multiple-input Multiple-output)

The first of the 5G technologies that could upgrade networks' capacity is the Massive MIMO Radio Access Technology (RAT). The technology aims to increase the number of antennas that are deployed at a Base Station (BS), so the same happens with the processing gain. With this method Massive MIMO serves N UEs at the same time can meet the latency and reliability challenges that are demanding for realizing TI [33].

The most important features of massive MIMO connected to URLLC [34]:

- Higher Signal-to-noise Ratio (SNR) links

- Links that are resistant to fading
- Extreme spatial multiplexing capability

The first two properties guarantee high reliability and the avoidance of unnecessary retransmissions. The deploying of a large number of to a BS provides us many more spatial diversity paths that are created [34]. Moreover, according to [35], capacity could be increased 10 times and at the same time, energy efficiency could be improved by 100 times.

The combination of Massive MIMO and URLLC will realize TI. Furthermore, according to [36] the potential benefits of taking advantage of Massive MIMO for the realization of time and mission-critical communication, and consequently for the development of TI, have also been explored.

2.1.5.2 Millimeter Wave Communications

Another 5G technology that could play a major role is related to the use of higher frequencies in the millimeter-wave band. The increase of the frequencies will lead to the increase of the bandwidth which will lead to increased data rates. Furthermore, the channels in the MMW band (30-300 GHz), offer hugely more available bandwidth which is available as soon there is a need.

Millimeter Wave will be used by 5G technology for the bandwidth that is of no use and can be exploited. There exist disadvantages in the mm-wave that make its use difficult for example the constraints met in the hardware infrastructure. The deployment of indoor base stations and the small cells that can be used can address the possible drawbacks. [35]. Real-time applications can be promoted as higher bandwidth, capacities and as a result, lower latency will be noticed (Figure 30).

2.1.5.3 5G Network Slicing

5G systems cover a wide range of services, from very demanding applications such as those related to the field of health to applications related, to the field of entertainment, which have high demands, but without serious consequences beyond that of bad user experience. One solution that is widely accepted is the implementation of an architecture that changes the forms of the network, depending on the service offered, leading to the concept of network slicing per service. An important role in the implementation of this architecture will be the use of technologies such as SDN and NFV, which can be used to simultaneously provide a variety of different services to a common underlying physical infrastructure [37]. The main components of the proposed architecture are depicted in Figure 14.

The main components of network slicing are the following:

- Infrastructure Layer: refers to the physical network infrastructure spanning both the radio access network and the core network. It also includes deployment, control, and management of the infrastructure; the allocation of resources (computing, storage, network, radio) to slices; and the way that these resources are revealed to and can be managed by the higher layers.
- Network Function Layer: encapsulates all the operations that are related to the configuration and life cycle management of the network functions that, after being optimally placed over the (virtual) infrastructure and chained together, offer an end to end service that meets certain constraints and requirements described in the service design of the network slice. In this section, the SDN end NFV technologies are placed.
- Service Layer and MANO: Perhaps the most important element that distinguishes network slicing in the context of 5G from other forms of slicing that have been considered in the past. It has the following two layers:
  - ➢ A service layer that is directly linked to the business model behind the creation of a network slice.
  - ➢ Network slice orchestration for the hyper vision of a slice’s life cycle.

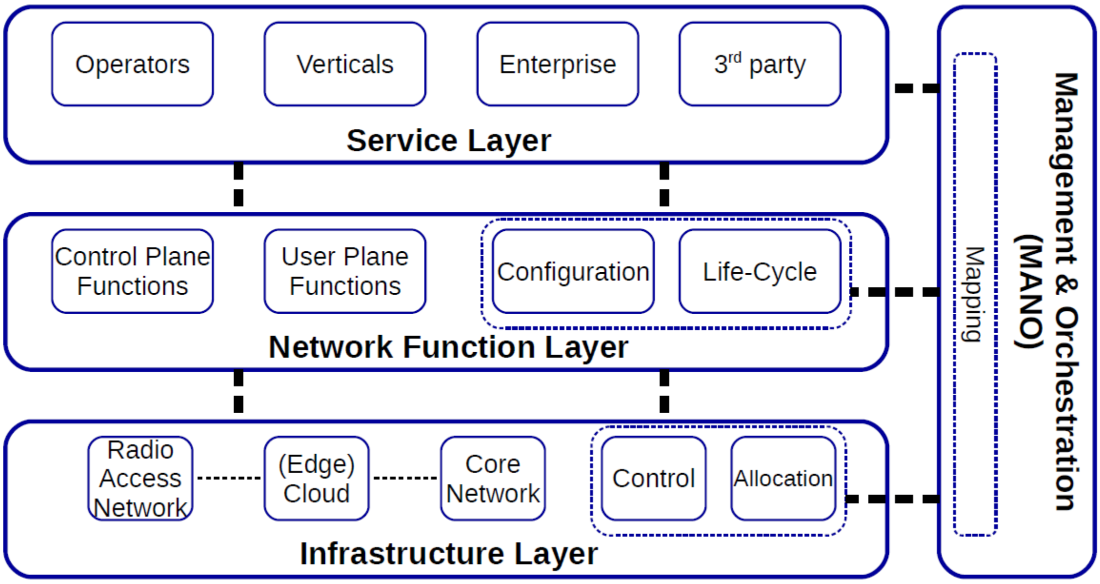

Figure 14 Generic framework representing various 5G architectural proposals [37].

2.1.5.4 Extremely Small Cells, Ultra-dense Networks, and Heterogeneous Networks

Finally, we will refer to the last 5G technology which is the development of extremely small cells to increase the network’s capacity. Picocells and femtocells are included in future networks. More users will be assisted within the same spectrum as there will be an increase of smaller base stations. This, of course, calls for an increase in the number of backhaul links that will be wireless or wired [33]. BS densification will contribute radically to the deployment of URLLC. The BSs will be placed in short distances to each other; following the population of the territory and if it’s urban or not, users will achieve many associations so the resource allocation that a user can accomplish will increase. All the above advantages will enable reliable, fast, secure, and ubiquitous connections that are essential for the realizations of TI vision [34].

2.2 Firefighting Drones

2.2.1 Drones in general

Drones were initially developed for military use, their goal was to provide intelligence and to accomplish high-risk air strikes, behind enemy lines, in order to provide efficiency without human losses. Nevertheless, nowadays we can use drones in various applications where we don’t want to put in danger personnel, in difficult terrain.

2.2.1.1 Definition

UAVs, also commonly known as drones, are aircraft piloted by remote control or embedded computer programs without a human on board [21].

2.2.1.2 Drones Characteristics

Drones have specific characteristics accordingly to the usage and the type [38], [39]. Consequently, a drone that will be used in goods delivery, accordingly the distance, the payload, the desirable flight time, e.t.c the drone will have different size, power supply system (batteries, gasoline) so in tables1 and 2 are depicted different types of drones with their specifications.

Table 2 Technical specifications of some multirotor drones. Maximum practical use payload < 30 kg [39].

Drone	Company	Type	Weight (Kg)	Dimensions (mm)	Folded Dimensions (mm)	Propeller/ Rotor Number	Speed (Km/h)	Payload (Kg)	Flight Time (min)	Website
PD6B-type2	Prodrone	hexacopter	19.5 (batteries included)	L 1874 W2060 H 474	L 1348 W600 H 474	6	max 60	No payload	35	prodrone.com
								10	15	
								20 (practical use)	10	
GD-40X	Gryphon	X8 octocopter	12 (dry weight) 40 (max takeoff weight)	D 1400	D 1000 detachable arms retractable gear	8 (4 + 4) coaxial propellers	max 50 avg 40	No payload	50	gryphondynamics.co.kr
								22–25	24	
Vulcan D8	Vulcan	X8 octocopter	16 (dry weight) max 55	L 1400 W1150 D 1670	L 1400 W400 h 500	8 (4 + 4) coaxial propellers	max 80 avg 30/40	No payload	>30	vulcanuav.com
								10	22	
								20 (practical use)	14	
Griff 135	Griff Aviation	X8 octocopter	max takeoff weight 135	L 2410 W2260 H 470	L 1440 W770 H 470	8 (4 + 4) coaxial propellers	-	No payload	>30	griffaviation.com
								30 (max 50)	25–30	

Table 3 Larger and heavier drones. Cargo Air Vehicles and Passenger Autonomous Air Vehicles [39].

Drone	**Company**	**Type**	**Speed (Km/h)**	**Payload (Kg)**	**Website**
Pegasus 120	Israel’s Aeronautics	octacopter	80	45	cp-aeronautics.com
EHANG 216	Ehang	AAV	130	220	ehang.com
Griff 300	Griff Aviation	X8 octocopter	60 (avg 50)	226	griffaviation.com

2.2.1.3 Drone Sensors

Every drone has some common sensors, to receive data and transmit them to the operator, who evaluates them. Some of those sensors, regardless of the application are the following [40], [41]:

- Inertial Measurement Units (IMUs): Fuse information from different sensors to provide measurements that can be used to calculate the orientation, pressure altimeter, and velocity of the UAV.
- Tilt Sensors: The sensor which senses the angle of inclination of the device housing it concerning the downward force of gravity is known as a tilt sensor. It is also known as a tilt switch or tip-over switch. Tilt sensors, combined with gyros and accelerometers, provide input to the flight-control system to maintain level flight. This is extremely important for applications where stability is paramount, allowing the detection of small variations of movement.
- Accelerometers: Are used to determine the position and orientation of the drone in flight.
- Magnetic Sensors: In drones, electronic compasses provide critical directional information to inertial navigation and guidance systems. Anisotropic magneto resistive (AMR) permalloy technology sensors, which have superior accuracy and response time characteristics while consuming significantly less power than alternative technologies, are well-suited to drone applications.
- Gyroscopes – determine the rate of rotation, or angular velocity and tilt.

2.2.2 Drones Applications in Disasters

Drones can be used in various applications and specifically for disasters, this is happening because UAVs can be used as aerials platforms with various sensors installed. Thus, gives us the ability to attempt disaster operations in dangerous environmental conditions by using UAVs without exposing in danger personnel and expensive equipment [21]. Some of the main applications that drones are used to encounter disaster are clarified in the sub-chapters follows.

2.2.2.1 Spread of Hazardous Materials and Nuclear Accidents

One of the applications that drones are widely used is the spread of hazardous materials or radioactivity after an accident [21], [42]. The spread of hazardous materials is common after accidents in factories or underground gas pipes. Our main goal is to identify the nature and the direction of the spread of liquids or gaseous materials. The nature of drones as aerial sensors platform allows us to use them to identify the hazard material and the direction of the pollution at the early stages of the accident (Figure 15).

Figure 15 Fix wing drone equipped with chemical sensors [21]

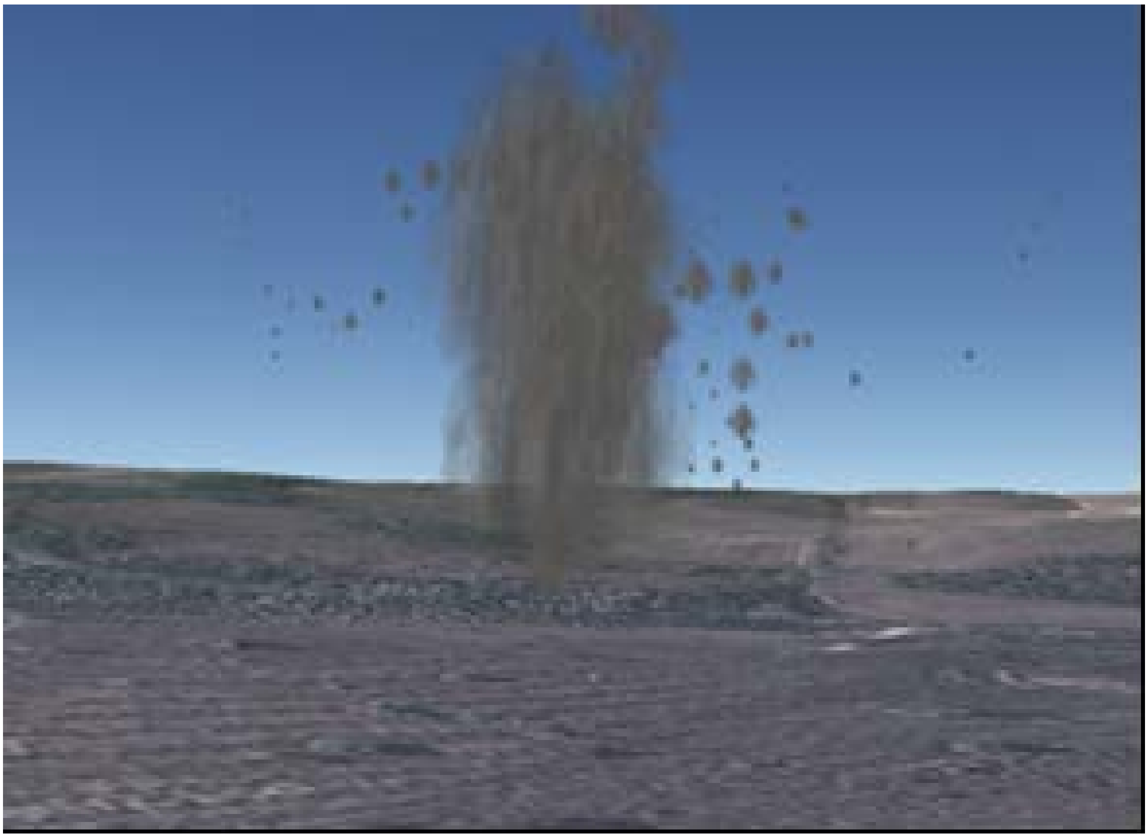

Figure 16 3D model of the detected nitrogen-monoxide [21].

Moreover, by the ability of drones to fly over the area of interest by safe distance, for the operator, to obtain three-dimensional images so-called rheological curves (Figure 16), quickly and objectively, gives the ability to the competent service, to manage more efficiently the disaster.

In addition, in nuclear accidents, we can obtain data about the level of the radioactivity of the area of interest by installing a suitable sensor on a drone, which has the ability to fly over the affected area, without using humans.

2.2.2.2 Earthquakes

After an earthquake UAVs could help by mapping injured buildings that can be characterized by an international standard [21], [42]. Based on the scaled ruins special rescue teams can optimize their work depending on the rate of assumed (measured) surviving holes. Since the chance of survival is drastically reduces in time the rapid mapping can effectively raise the rescued lives (Figure 17).

2.2.2.3 Floods

Mainly drones can aid the crisis management forces by observing the flooded area, finding damaged buildings, trapped humans, or even predicting how the flood area will proceed [15].

2.2.2.4 Forest Fires

Forest fires are a domain that UAVs could be used to aid the ground forces to early detect or even to extinguish a fire [21], [42]. Forest fires are usually happening on hard terrain where humans and vehicles can move difficult, drones can fly over the areas, and with their sensors, (e.g. smoke detectors, thermal cameras, gas detectors) can provide, in real-time, valuable information about the fire. Moreover, as we will describe in the chapters that follow, drones can help also to fire extinguish in more active ways.

Drones could aid in the reduction of the casualties of the firefighters that are falling on duty, during a forest fire. (according to [43] only in Greece do we have 39 firefighters lost during forest fires). Also, another sector that drones could aid is the loss of expensive equipment and the use of expensive in-use machinery (e.g. manned aircraft to patrol over forests) to reduce the cost of forests observation (Figure 18).

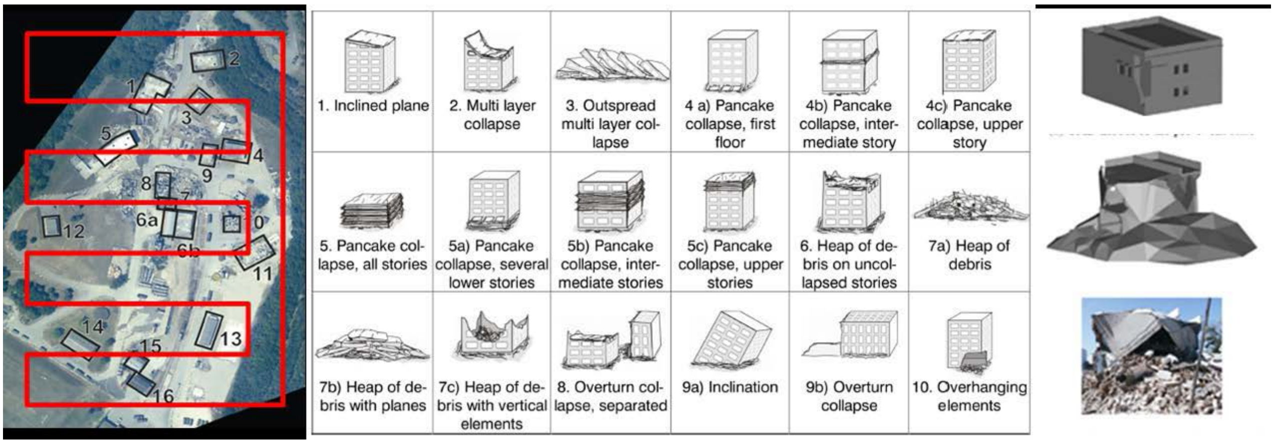

Figure 17 Mission planning above the affected area (left), classification of a collapsed building (middle), and 3D modeling [21].

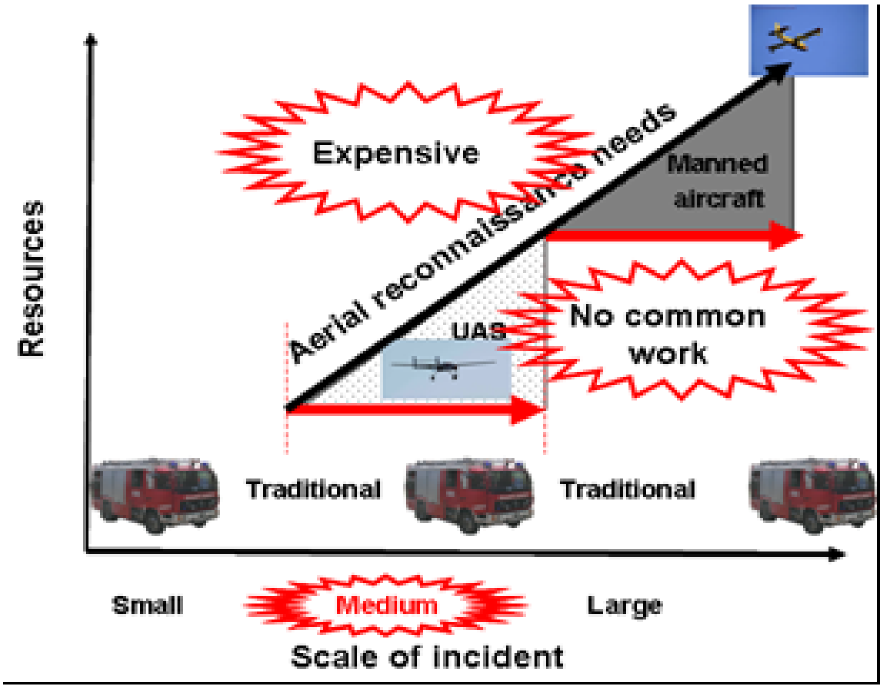

Figure 18 Efficiency of drone (UAS) application depends on fire size [21].

2.2.3 *Firefighting Drones Applications*

2.2.3.1 Early Fire-Detection

The most common application that UAVs are being used to aid firefighters in their mission is the early detection of forest fires. Therefore, UAVs at the early stages of their use were used as reconnaissance platforms, for military courses. To achieve that they used special, high-efficiency FLIR cameras to achieve the best results. In fact, according to [44], during the massive wildfires of California in 2007, providing firefighters with up-to-the-minute data on the many conflagrations, helped in the coordination of firefighting efforts that spared many lives and structures—including the venerable Palomar Observatory. Within 15 minutes, fire command centers all over San Diego received color-coded Google Map images that indicated the temperature on the ground at different locales (Figure 19).

Moreover [45] illustrates a typical UAV-based forest fire surveillance system in Figure 20, which is composed of a team of UAVs, different kinds of onboard sensors, and a central ground station. Also proposes a fire detection method for the application of UAV-based forest fire surveillance using IR camera, by using both brightness and motion features of fire in IR images to improve the accuracy and reliability of forest fire detection.

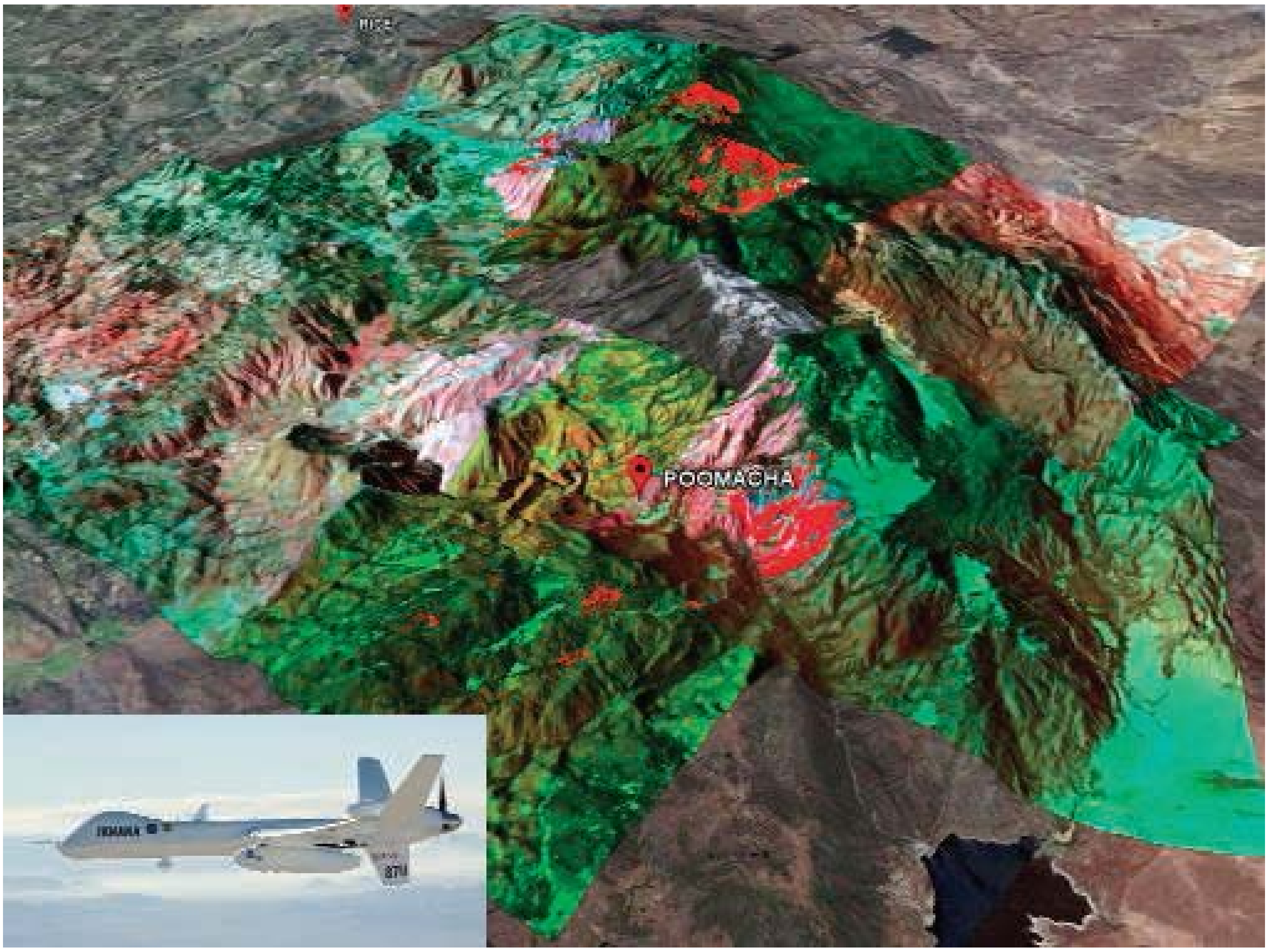

Figure 19 Thermal-infrared images from the unmanned Ikhana (inset) helped firefighters battle the Poomacha fire near San Diego's Palomar Observatory [44].

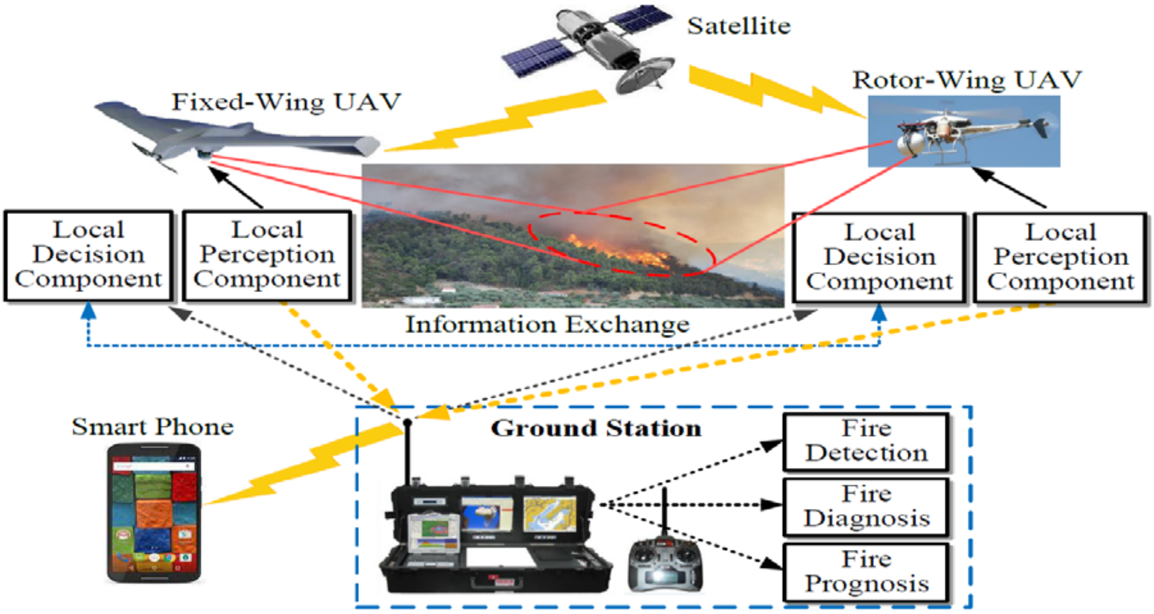

Figure 20 Schematic illustration of the UAVs-based Forest fire surveillance system [45]

2.2.3.2 Fire-breaks Creation

Another domain in which drones could play a significant role in aiding wildfire fighting is the creation of fire breaks (Figure 21). Fire-breaks are land zones that are being controlled burned to stop the fire the time arrives. According to [46] a drone like this could drop 400-450 golf-size balls, called Dragon Eggs, which contains potassium permanganate, and just before they are released, they are given a pin injection of anti-freeze. The reaction between the two chemicals ignites the spheres after they hit the ground. The eggs can set fires ahead of an advancing wildfire in hard-to-reach places, denying it fuel. It has been proven that dragon balls are a much more effective barrier against the spread of the wildfire than the traditional methods and safer since the operator is miles away and he’s fighting a fire in an extremely dangerous environment by distance.

Figure 21 Fireball-dropping drone [46]

2.2.3.3 Fire Extinguish

Finally, UAVs could be used in extinguishing wildfires at their early stages. It’s easily understood that if a wildfire could be detected in its early stages (Figure 22), where the Heat Release Rate (HRR) is small, is much more manageable. At those early stages, an equipped drone could play a vital role in wildfire extinguish.

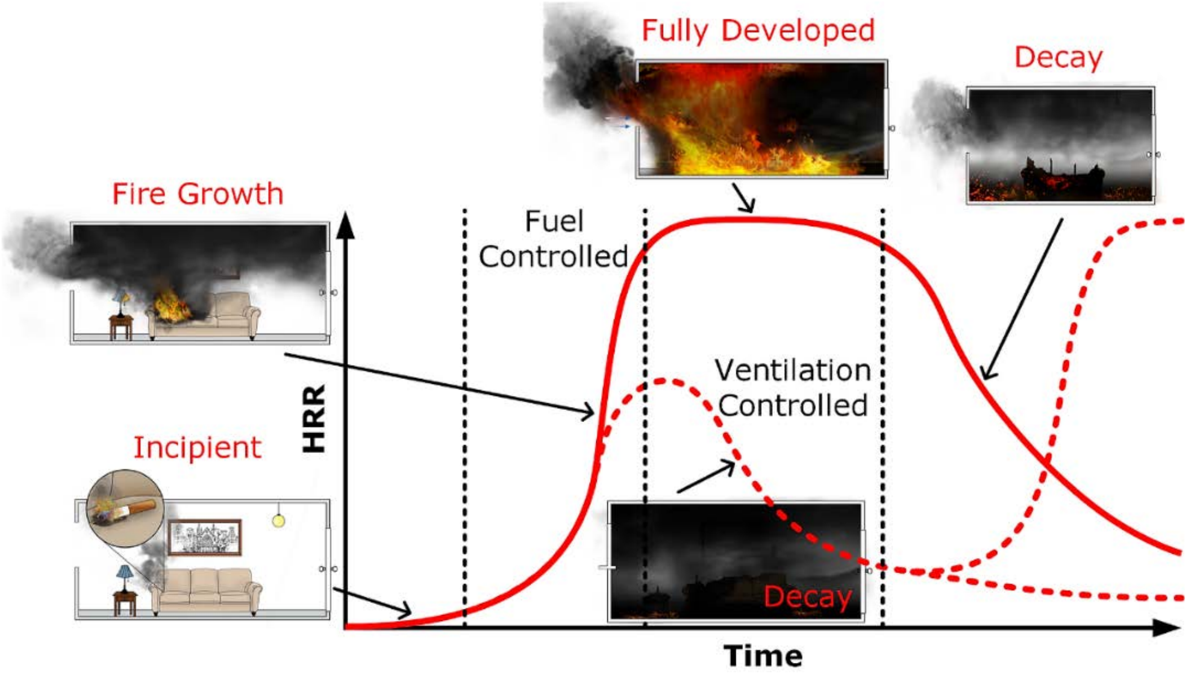

Figure 22 Four stages of the fire [47]

As an equipped drone, we mean which has the means to extinguish fires, especially at the early stages. According to [48] a drone could carry fire extinguishing balls (Figure 24) to extinguish fires, in their early stages. Fire extinguish balls are 6 inches balls, which weigh 1.3 Kgr and have minimum maintenance needs (5year guarantee). They contain chemicals which in the right temperature are being exploded and release the chemicals to extinguish the fire. The latest years there are at least two major companies that produce such material and also because of the usage drone produces implement models with the ability to carry a payload of 16 fire balls [49]. The chemicals that fire balls contain are harmless for humans and the environment and the “surgical” way of use make them also an economical way to extinguish a small fire before it could be a massive wildfire [50].

In addition, nowadays a lot of companies with remarkable research work are producing prototypes that have the ability to extinguish fires. One of them is described in [52] is EHang, which produced a large payload intelligent, firefighter drone, based on a transportation model, the EHang 216F, which has a maximum flight altitude of 600 meters and can carry up to 150 liters (40 gallons) of firefighting foams and six fire extinguisher bombs in a single trip. The firefighting eVTOL uses a visible light zoom camera to identify the location of the fire; it then hovers precisely in position and uses a laser aiming device to fire, the fire extinguishing "bombs" and the firefighting foam (Figure 23).

Figure 23 The EHang 216F [47]

Figure 24 Commercial Fire Ball (left) Demonstration of Fire Ball (right) [51], [50]

2.3 The role of TI in remote operation

Teleoperation (or remote operation) indicates the operation of a system or machine at a distance. It is most commonly associated with robotics and mobile robots but can be applied to a whole range of circumstances in which a device or machine is operated by a person from a distance [53] [54]. Obviously, teleoperation has similar requirements with TI. For instance, when a surgeon operates from a distance needs (Figure 25):

- Real time information (visual,audio)
- Ultra-reliable connection
- Secure connection

It is easily understood that such vehicles for example should provide data in practically, rea-time with the minimum packet loss and with the maximum security.

Moreover, as the applications are being expanded, the requirements are changing too, and in most cases become more demanding. Furthermore, the value of TI in teleoperation could be more valuable in healthcare where a surgeon should have haptic feedback, of the patient, like temperature, hardness of the tissue, etc.

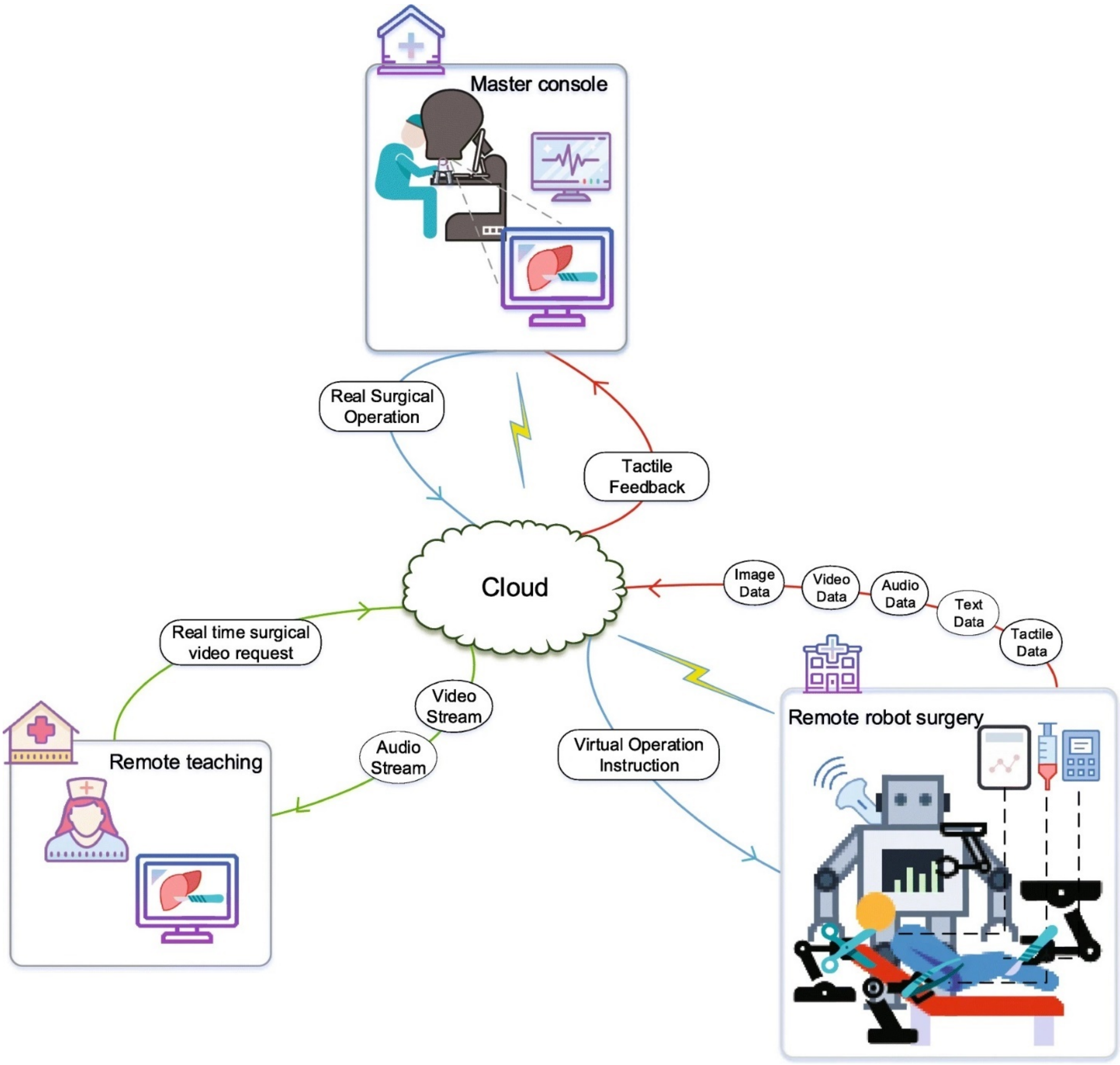

Figure 25 Surgery teleoperation scenario [55]

3

Firefighting Drones Using the Tactile Internet

Drones in general and especially firefighting drones have all the necessary equipment to accomplish a fully autonomous flight, also they can even detect fires by using deep learning techniques [56]. But what is the need to follow TI principles and why we should provide haptic feedback to an operator? Those are some of the questions that we are called to answer in the chapter follows.

3.1 Firefighting Drones and Tactile Internet

Firefighting drones are made to act over a hostile, high-temperature environment, with a microclimate that produces high tense heat winds, almost vertical columns of airwaves and at the same time drones should be accurate to drop their payload exactly over the fire because the fire extinguishing balls have a coverage of almost 2 cubic meters as depicted in table 1. So is vital for the mission to be accomplished the operator to be able to feel all the immediate changes over the drone in real-time.

Table 4 Data collected during experimental tests [48]

Ball's number	Time for ball activation in second	Effective extinguishing area in Cubic meter
1	7	2
2	6	2.1
3	5	1.8

3.1.1 Fires Microclimate

During wildfires it is common for Convection columns (Figure 26) to be created, convection column, "*is an ascending column of gases, smoke, and debris produced by the heat of a fire that generates powerful updrafts. The height of a column into the atmosphere depends on the degree of atmospheric instability, heat output of the fire, and speed of higher altitude winds. The heat also propels moisture that condenses into pyrocumulus clouds”* [57]. This effect is produced because of the physiology of the wildfires, as fires burn a column of hot air rises into the atmosphere, at the same time cool air quickly rushes in to replace the gap of air, finally, once the smoke and thermal waves reach a certain height in the atmosphere water vapor will create a pyrocumulus cloud [57], [58].

Moreover, another violent effect that takes place during a wildfire is Downburst, (Figure 27) which *"is a strong ground-level wind system that emanates radially from the surface landing point in a straight line in all directions. They can contribute to very sudden changes in surface winds, moisture, and temperature"* [57], [58].

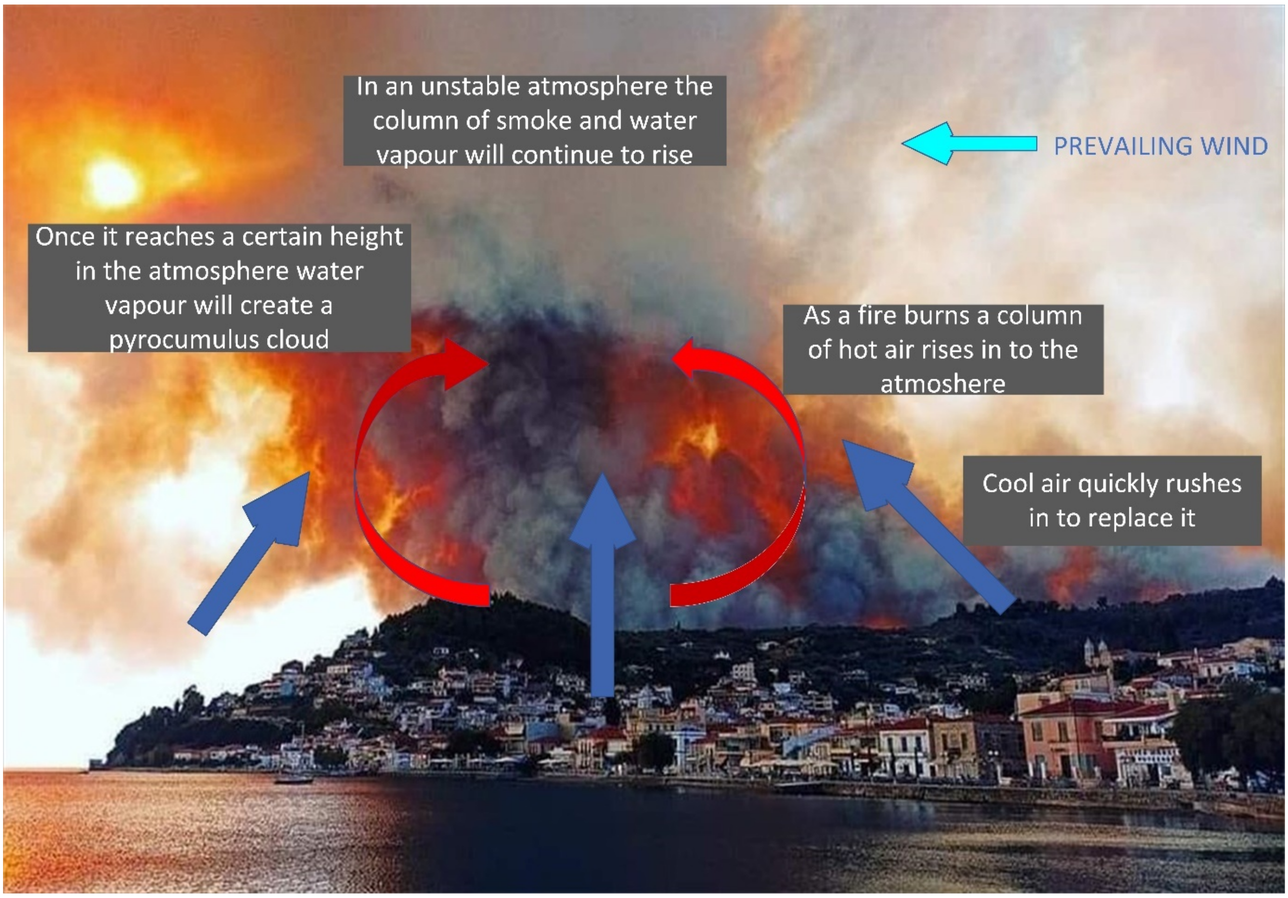

Figure 26 Creation of Convection columns over Wildfire based on [57]

Figure 27 Downburst effect based on [57], photo by Kosmas Koumianos.

As it is easily understood those special climate circumstances play a cardinal role in the aerodynamic behavior of drones, which can change dramatically because of the violence of those phenomena. Consequently, the change of the aerodynamic behavior of the drones should trigger a procedure, that is described in chapters that follow, in which the drone should fall into from autonomous flight to the manual, with haptic feedback for the operator to be aware from the immediate changes on the slave domain in real-time.

3.1.2 Latency

Although according to [59] latency in drone applications should be from 20ms to 40ms, should be noticed that those prices refer to surveillance applications with low requirements applications. Firefighting drones have high requirements in latency because of the active role in wildfire extinguish. Moreover, we should keep in mind that because of the accuracy needed in firefighting drones, the speed of UAVs and the special microclimate of wildfires makes us believe that a latency closer to tactile standards from 1ms up to 5ms is needed as depicted in Figure 28. Moreover, as it is easily understood the high latency, will make firefighting drones inefficient, due to the vertical drop of accuracy and the possible cyber-sickness, that may be caused to the operator. The cyber-sickness may cause drone crashes, which are economically unprofitable due to the high cost of specialization.

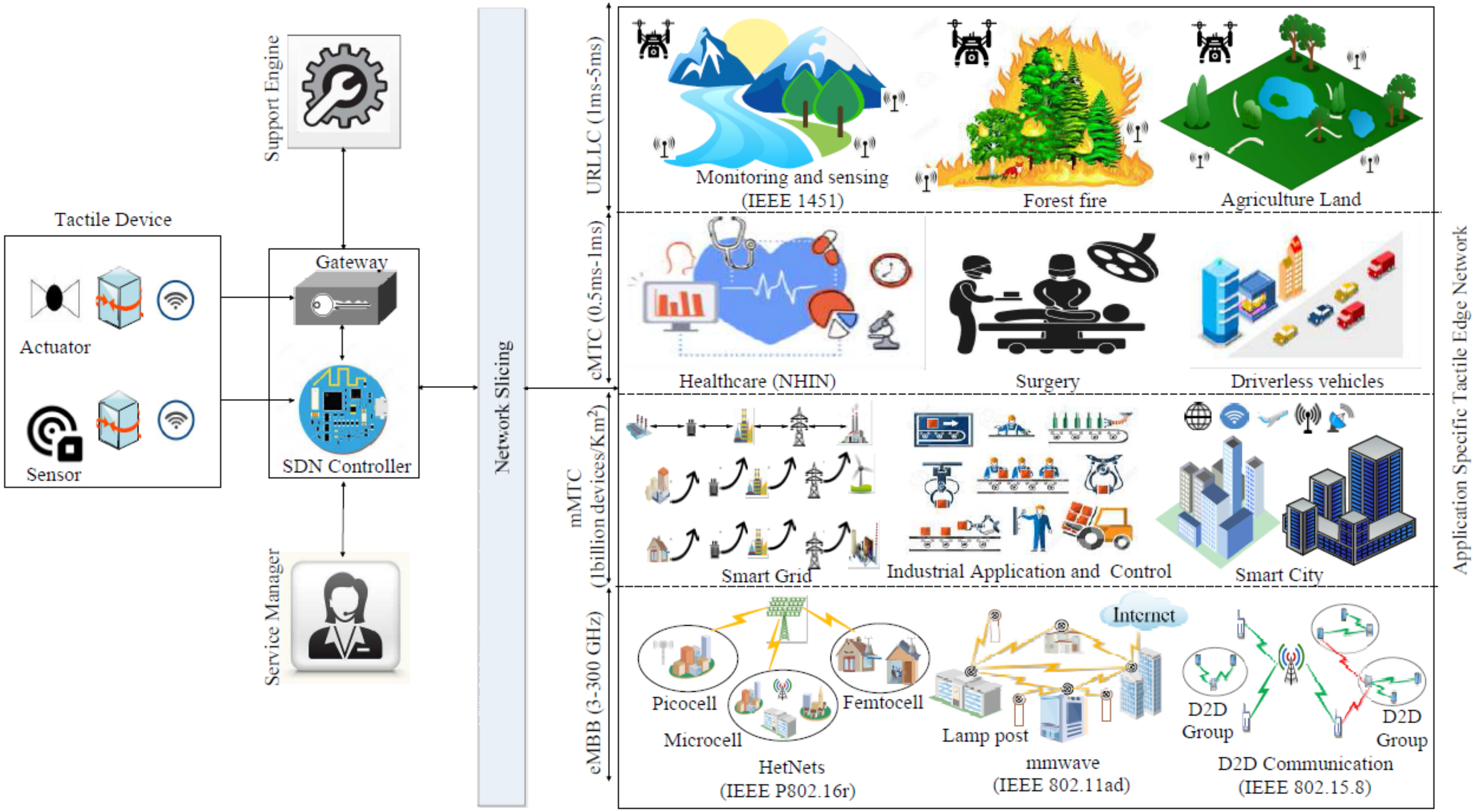

Figure 28 Application-oriented architecture of TI [60]

3.2 Drones Architecture Following Tactile Internet architecture (P1918.1)

The general architecture of TI is outlined in Figure 29 having three domains:

- Master domain,
- Network domain, and
- Slave domain

The general architecture of TI is depicted in Figure 29 and is analyzed as follows.

3.2.1 Master Domain

It comprises two basic components, a human operator and a human-system interface (HSI). HSI is a haptic device (intelligent robot). The haptic device permits users to send and receive sensations such as touch and feel. Its function is to receive the human input and convert it into the tactile input by using appropriate coding, ie, tactile coding. Moreover, its primary function is to direct and control the operations of the slave domain. [60], [13] ,[8] , [10], [7], [61], [62]. In firefighter drones, the master domain role is being played by the operator who will take control when needed.

3.2.2 Network Domain

It provides two-way communication between the master domain and the slave domain. The main aim of this domain is to kinesthetically, ie, physically couple the human operator with the remote environment. The network requires ultra-reliable, ultra-responsive, high-availability internet and secure connectivity for real-time haptic communication [60], [13] ,[8] , [10], [7], [61], [62]. The network domain of TI architecture has the following elements:

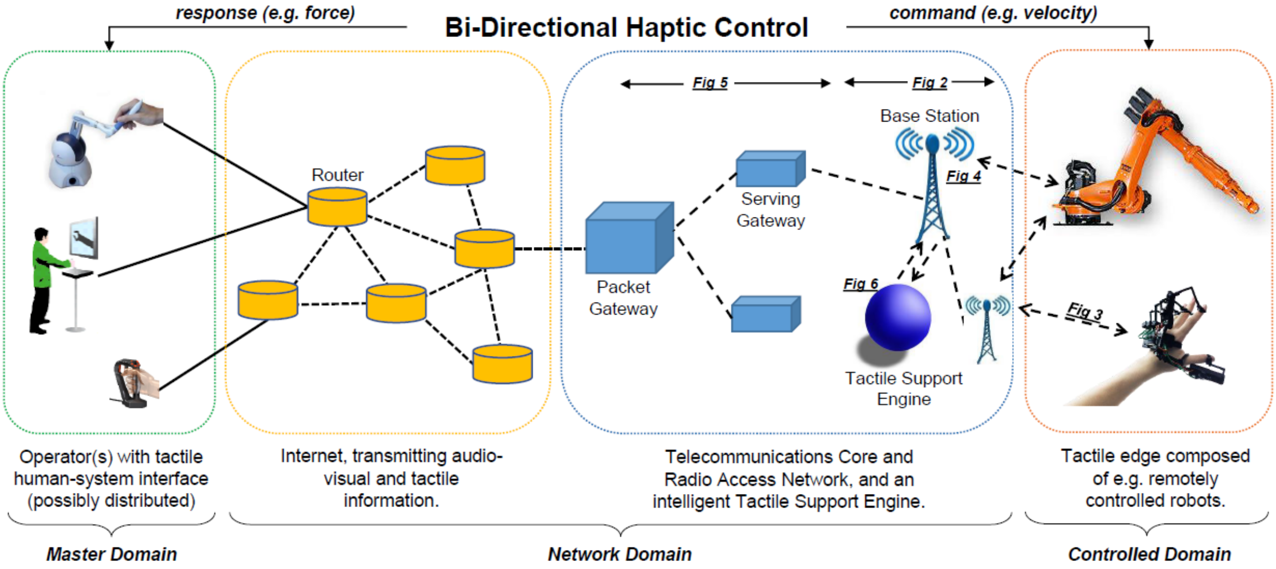

Figure 29 Functional representation of TI architecture [12]

- Router: In TI architecture, the router is used to transport audio-video and tactile information.
- Packet gateway (PGW): Acts as an interface between the LTE and the other packet data networks.
- Serving gateway (SGW): Routes data packets and maintain the IP barrier information of user equipment (UEs).
- BS: It is a radio transceiver that acts as a central hub for connecting wireless devices to the network through an antenna.
- Tactile support engine: This element of the network domain has artificial intelligence (AI) algorithms for anticipating the haptic experience.
- In the firefighting, drones use case, because of the low coverage of the territories that drones operate a drone that plays the relay role may be used in close cooperation with 5G mmWave communications, Figure 30, [63], [23].

3.2.3 Slave Domain

Slave domain: It consists of a teleoperator, ie, the supervised robot. It is directly operated or controlled by the human operator in the master domain bypassing various control signals. The function of the teleoperator is to interact with the remote objects [60], [13] ,[8] , [10], [7], [61], [62]. In firefighting drones use case, the role of the slave domain is being played by the drone itself.

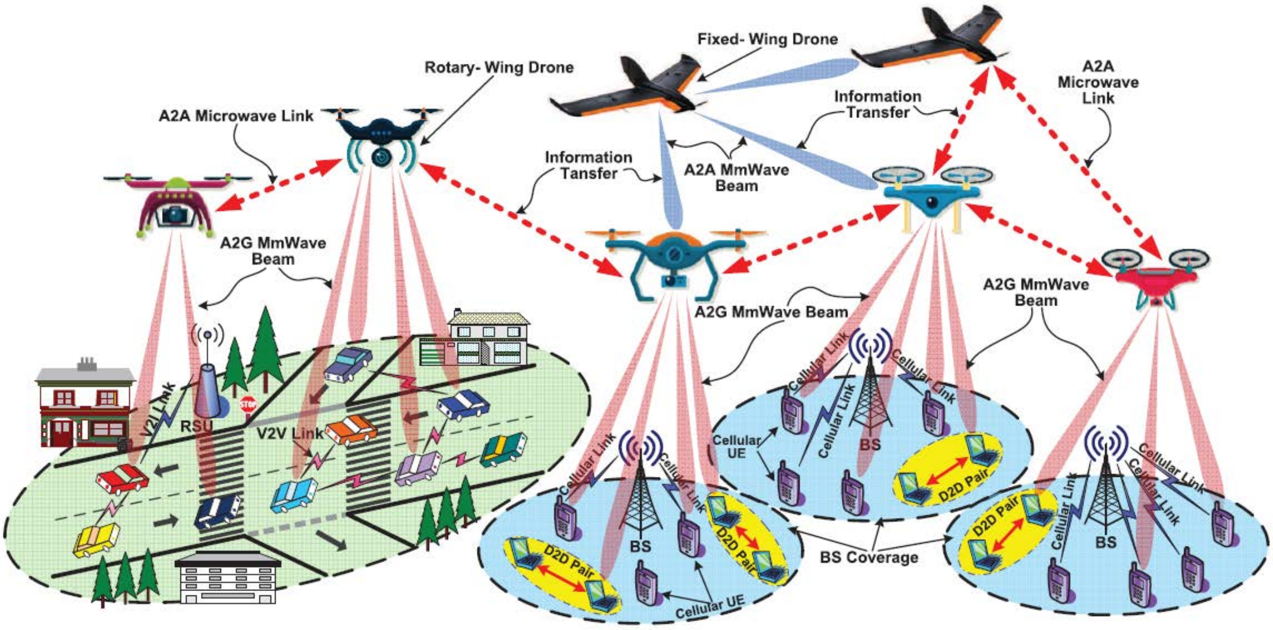

Figure 30 Illustration of 5G mmWave communications for UAV-assisted wireless networks [63]

3.3 Architecture and State Machine of the IEEE P1918.1 Standard

In this subchapter, we will quote some key aspects of the architecture, and the operational state machine is defined within the IEEE 1918.1 baseline standard [3].

3.3.1 Architecture

The architecture should meet requirements, such as the supporting various use cases and QoE hence the architecture should be/provide:

- Generic and modular.
- Interoperable.
- Advanced operation
- Advanced management functionalities.

The architecture is depicted in Figure 31 and Figure 32, which cover the various modes of interconnectivity network domains between two tactile edges. Each tactile edge consists of the entities as follows:

1) Tactile Device (TD) – The tactile device is the basic entity of the tactile edge. TDs are used to provide sensing, actuation, haptic feedback and are composed of as follows:
   - Sensor (S) and actuator (A) are devices for sensing-actuation functions.
   - Sensor nodes (SN) or actuator nodes (AN) are devices with networking modules.
   - Human System Interface Node (HN), converts human input into haptic output.
   - Controller Node (CN) runs control algorithms for developing all the necessary procedures of a system of SNs and ANs.
2) Gateway Node Network Controller (GNC) - The GNC is responsible for activating agreement between the IEEE P1918.1 standard and other emerging standards and is composed of as follows:
   - The gateway node (GN) offers enhanced networking capabilities. GN is responsible for forwarding user plane data.
   - The network controller (NC) is responsible for:
     - ➢ Control-plane processing including intelligence for admission and congestion control.
     - ➢ Service provisioning.
     - ➢ Resource management and optimization.
     - ➢ Connection management.
3) Support Engine (SE) – Offers computing and data storage abilities to optimize the performance of the entire TI system and meet the latency and reliability requirements. The SE will run advanced algorithms, implement AI procedures, to act operations that need a lot of resources and/or are energy-demanding to be done in the TD.

SE can be installed locally within the tactile edge to increase the response rate for requests from TDs or GNC, and/or it can be installed remotely in the cloud while providing services to the tactile edges and network domain.

4) Tactile Service Manager (TSM) - Defines the requirements of the service between the two tactile edges and disseminates this information to the nodes in the entire network architecture. The tactile service manager is an optional entity. Its existence is dependent on the use-case and the underlying connectivity technology.
5) User-Plane Entity (UPE) - An entity that handles the user-plane functions for the tactile edge.
6) Control-Plane Entity (CPE) - An entity that handles the control-plane functions for the tactile edge.

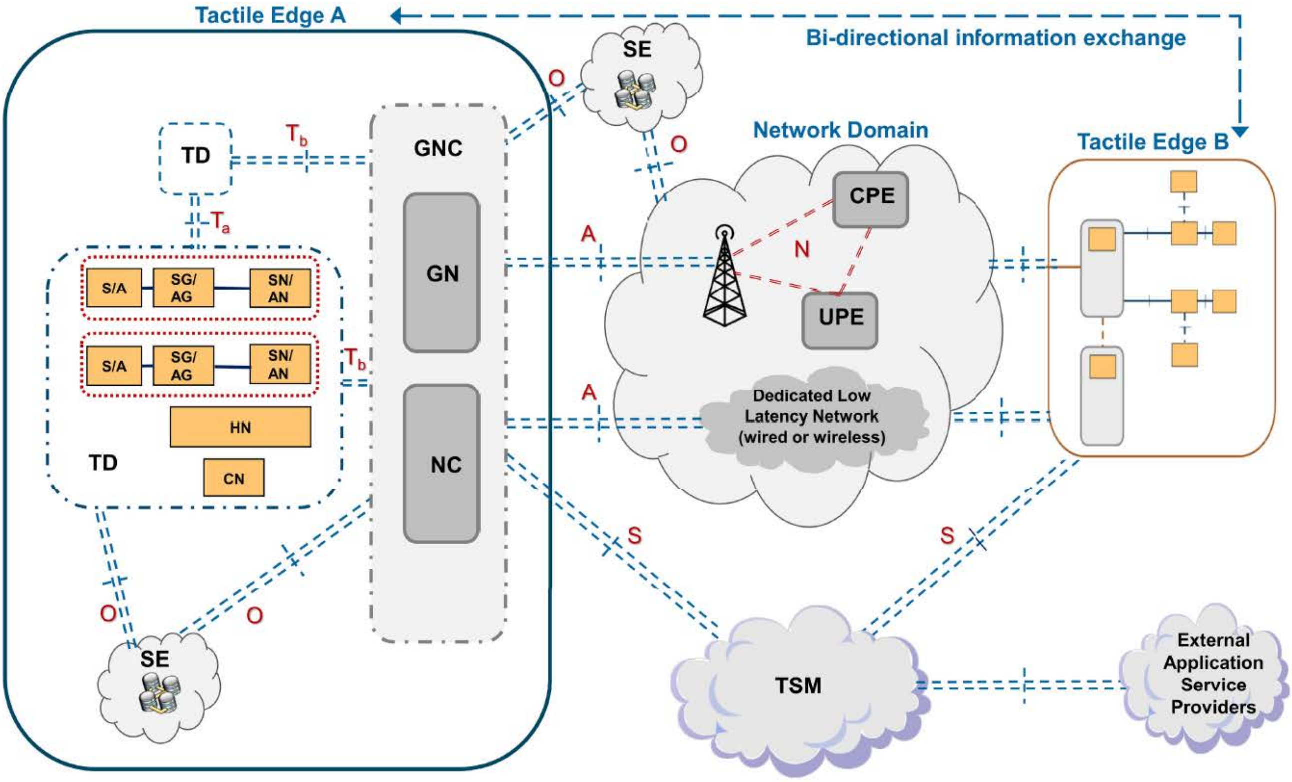

Figure 31 IEEE P1918.1 architecture with the GN and the NC residing as part of the tactile edge [3].

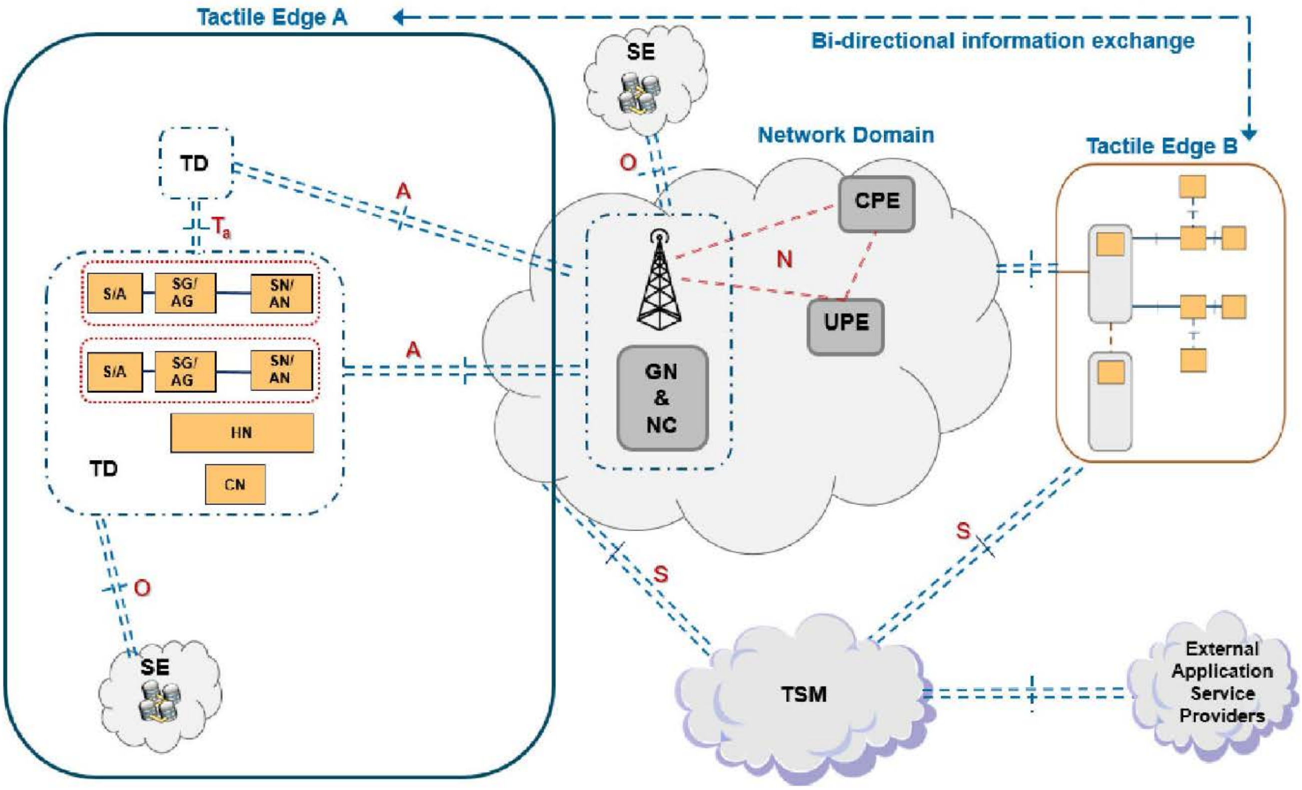

Figure 32 IEEE P1918.1 architecture with the GN and the NC residing as part of the network domain [3].

3.3.2 Interfaces

The basic interfaces that will support interactions between the basic elements in TI architecture are the following:

1) Access (A) Interface: Succeeds connectivity between the tactile edges and the network domain.
2) Tactile (T) Interface: Succeeds connectivity between components within the tactile edge.
3) Open (O) Interface: Succeeds connectivity between any architectural component and the SE.
4) Service (S) Interface: Succeeds connectivity between the TSM and the GNC.
5) Network Side (N) Interface: It is an interface providing internal connectivity between network domain components.

In terms of performance requirements, meeting the E2E QoS targets for active TI sessions imposes specific requirements on each of the interfaces along the path from source to destination TDs

Key Performance Indicators (KPIs) of the interfaces.

- The reliability of an interface measures its packet delivery performance
- The latency of an interface is a measure of its responsiveness

- The scalability of an interface describes its capability to cope and perform under an increased number of devices.

3.3.3 Bootstrapping of the Tactile Internet Service and Architecture Instantiation

Throughout TI operation, it is critical to define how TI communication will be accomplished, and the paradigms under which TI communication would be maintained and terminated.

That's why WG proposed three paradigms for establishing TI communication, focusing on how two TI components will bootstrap their remote communication and operation.

Crucial role in designing and implementation of the above-mentioned paradigms plays some factors beyond reliability and latency, such as:

- The availability of TI resources,
- The locality and distance between TDs,
- The availability and cost of delivery over communication infrastructures,
- The computing resources dedicated to TI operation,

The proposed three paradigms for establishing TI communication, focusing on how two TI components will bootstrap their remote communication and operation are summarized in Table 5[3].

Table 5 Contrasting the Operation and Architectural Requirements of the Three TI Communication Paradigms, Focusing on Resource Management [3]

TI comm. paradigm	Goal	Resource requirements	TI components required to initiate E2E comm.	Advantages	Disadvantages
Omnipresent	To enable a rapid association with TI infrastructure, via predetermined “access” gateways that are geographically and strategically spread	High needs in resource management	TD TSM CPE GNC	• Activates multiple time-sensitive use cases • Activates a seamless integration with NFV	• Reserving resources • Hard to scale • Security vulnerabilities
Ad Hoc	Minimal network maintenance	System memory on TI edge	TD GNC	Lower requirements of the resource management load	• Slower on establishing E2E communication • Risky on transient network failures
Hybrid	To be scalable and compact always available TI device	Upkeep of TSMs by using multiple surrogates	TD TSM GNC	• Fewer resources than Omnipresent • Faster establishing in E2E communication than Ad Hoc	Upkeep and scalability of surrogate TSM module

3.3.4 Tactile Internet Operational States

TI's vision is to support multiple use cases and applications with various requirements on reliability and latency. Apparently, because of the wide range of use cases, we shall meet use cases requiring ultralow reliability and latency to ones with the infrequent sampling of haptic data over less stringent networking modes. Consequently, it is crucial to define the operational states in which a TD would exist, throughout its active involvement, including all the phases of its function. The deterministic state transitions for the functional operational state machine for a TD establishing, maintaining, and terminating E2E communication with another TI component is depicted in Figure 33, and the states are summarized in Table 6, [3].

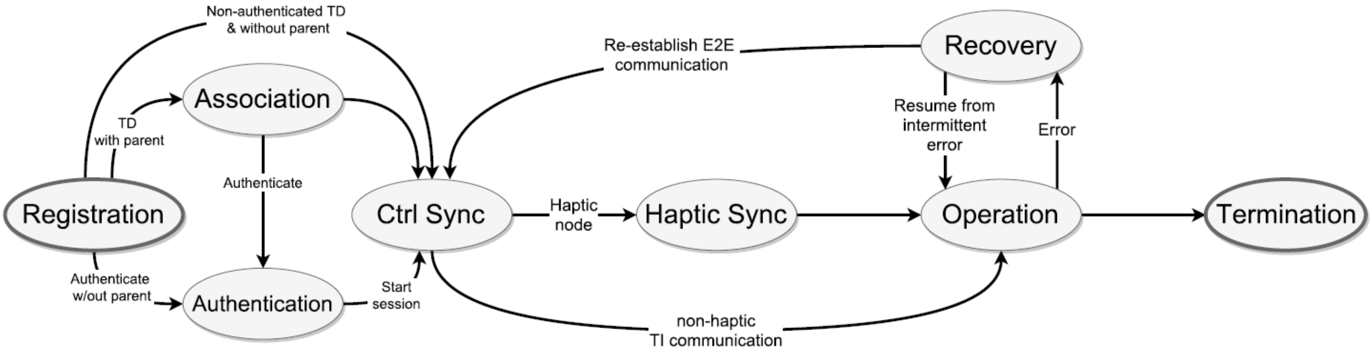

Figure 33 FSM depicting the deterministic state transitions for a TD establishing, maintaining, and terminating E2E communication with another TI component [3].

1) Registration – A TD device would start in the registration phase, which is the act of establishing communication with TI architecture. According to TI Communication Paradigms, the communication will be established as follows:
   - Omnipresent TI paradigm: The registration will be accomplished with a GNC, including TI components from the network domain, such as the TSM depending on the application. Hence, the “latching” point of the TD to trigger registration will be referred to as TI Anchor. At this stage, the TD is exploring TI architecture to initiate E2E communication. Particularly after this stage cannot perform any other functions beyond latching onto TI architecture.
   - Ad hoc - hybrid paradigm: This stage will use the TSM, probably via the GNC, to establish registration.
2) Association – Association, depends on the type of the TD:
   - If it is a lower-end SN/AN, then the TD will have a designated "parent" in its proximity, with which the TD will need to associate first. This state will ensure reliable operation and assist in connection establishment and error recovery.
   - If a TD device operates independently, then this would be an optional step.
3) Authentication - Some TDs, may have to be authenticated, this depends on the nature of the TD, in case it is mission-critical or a new one. In this state, a TD would communicate with the authenticating agent in TI infrastructure to accomplish authentication. The TSM is the main component that could determine this task, perhaps with assistance from the SE when needed. This state is optional.
4) Control synchronization - In the control synchronization state, which is mandatory, the TD will begin its E2E control synchronization, where it will examine and establish a link to the end tactile edge. At this state, the TD is not allowed to transmit or receive operational data but would focus on relaying connection setup and maintenance parameters.

This is a critical state, as it includes the path establishment and route selection phases of TI operation. Additionally, it will typically involve multiple tiers of TI architecture, which will communicate to ensure that a path that meets the minimum requirements set in the "setup" message is indeed available and reserved.

5) Haptic synchronization - If the TD in a TI session requires haptic communication, then the next optional state would encompass the specific communication and establishment of haptic-specific information, still before actual data communication. This state is vital in concluding on the codecs, session parameters, and messaging formats.
6) Operation - After the haptic synchronization state TD entities will then transition to the operational state, which is mandatory. This will be the most time-dominant state, as it will enclose all TI data communication.
7) Recovery - This is the mandatory state where one TD may detect a network error, in which designated protocols will take over error checking and potential correction mechanisms to attempt to reestablish reliable communication. If the error will be resolved, then the TD will transition back to the operational state, otherwise, the TD will transition back to control synchronization and rediscover whether or not an E2E path is indeed available under the operational requirements set out by the edge user.
8) Termination - Finally, once the TI operation is successfully completed, the TD will transition to, the mandatory, "termination" phase, in which all the resources that were previously dedicated to this TD are released back to the TI management plane.

Table 6 Describing the Operational States of a General TI Device, With Respect to Initiating Communication With Another TI Device [3]

State: Mandatory (m) | Optional (op)	Functional mandate	Functional capacity	TI node connected to:
Registration (m)	Register with TI architecture	TI probing	TI Anchor
Association (op)	Pair with “parent” TI node	TI association	TI Parent node
Authentication (op)	Authenticate with designated TI network-domain component	Exchange authentication messages	TI Authentication system
Control Synchronization (m)	Establish E2E connection (Set comm. parameters)	Communicate with other TI nodes for control only	TI nodes (Edge and core)
Haptic Synchronization (op)	Establish E2E haptic-specific parameters (session, codecs, etc)	Communicate with other TI nodes for control only	TI nodes (Edge and core)
Operation (m)	Carry out normal TI operation	Communicate with other TI nodes for data only	TI nodes (Edge and core)
Recovery (network) (m)	Recover from network failure	Communicate with other TI nodes for control only	TI nodes (Edge and core)
Recovery (operational) (m)	Recover from operational error or data/encoding errors	Communicate with other TI nodes for control only	TI nodes (Edge and core)
Termination (m)	Terminate connection	Tear down connection with TI Edge & TI Core	TI nodes (Edge, core, local parent)

3.4 Operational State Machine

In the sub-chapter that follows we will suggest a new state machine that is specialized in drones that operate over hostile territories like wildfires that losing control of the slave domain due to violent change of the aerodynamic behavior of the drone is a common situation. The deterministic state transitions of the operating machine are depicted in Figure 34 and a description of the operational states of a drone TI device is being clarified in Table 7.

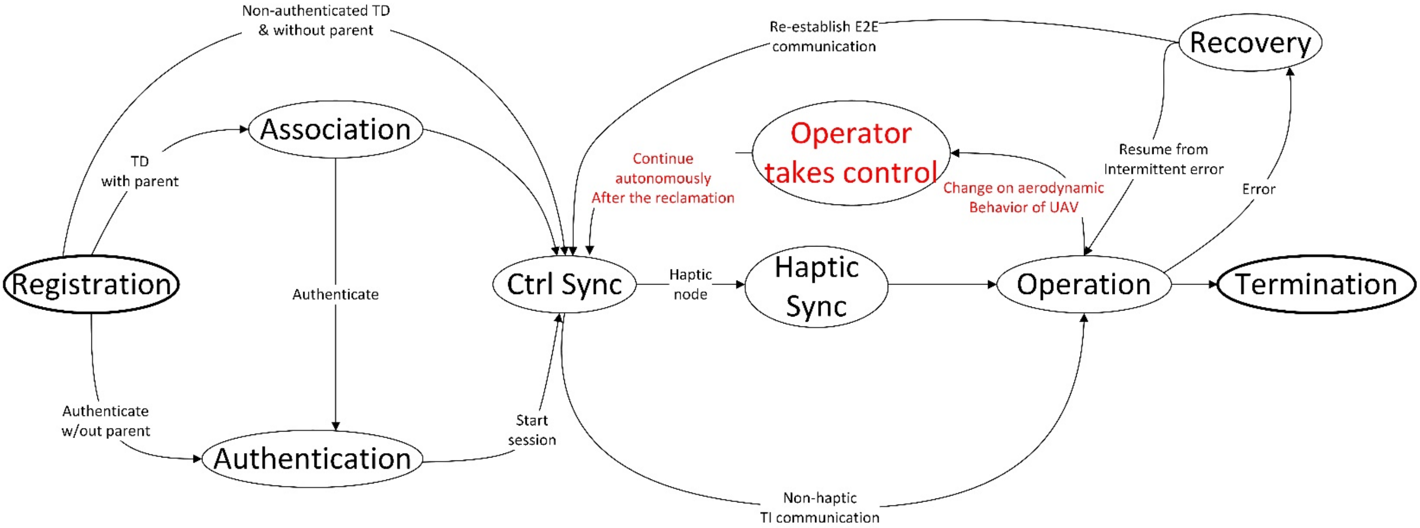

Figure 34 Operational State Machine based on [3].

1. Registration phase: According to [3] drone would start in the registration phase, which is defined as the act of establishing communication with TI architecture and will take place with a GNC, in cooperation with the TSM.
2. Authentication: At this state, drones need to be authenticated before being allowed to join/start a TI session, from TSM which is the main module that could carry out this task.
3. Control synchronization: At this stage, the drone will commence its E2E control synchronization to begin its E2E control synchronization, where it will examine and establish a link to the end tactile edge.
4. Haptic synchronization: At this state drone engaging in a TI session is proceeds an autonomous flight [64], but the haptic synchronization stage is mandatory for the TI system to be encompassed the specific communication and establishment of haptic-specific information on the codecs, session parameters, and messaging formats specific to this current TI session.
5. Operation: At this state drone will pass to the autonomous flight (operation) in which the E2E path has been established, it has met all connection setup requirements, and the tactile edges are ready to exchange TI information.
6. The operator takes control: In case that one or more of the sensors detect an aerodynamic anomaly (Table 9) on the behavior of the drone then the Inertial Measurement Unit (IMU) will trigger the procedures in order for the operator to take control of the drone and the next state will be
7. As soon as the conditions that led the drone to be unstable cease to apply, the TD device passes to control synchronization state to re-examine and re-establish a link to the end tactile edge, and

afterward, the TD will pass to the haptic synchronization to be encompassed the specific communication and establishment of haptic-specific information. Afterward, the drone will pass to the operation state and finally to the termination state Figure 34.

Table 7 Describing the Operational States of Drone TI Device, With Respect to Initiating Communication With Another TI Device based on [3]

State: Mandatory (m) | Optional (op)	Functional mandate	Functional capacity	TI node connected to:
Registration (m)	Register with TI architecture	TI probing	TI Anchor
Association (op)	Pair with "parent" TI node	TI association	TI Parent node
Authentication (op)	Authenticate with designated TI network-domain component	Exchange authentication messages	TI Authentication system
Control Synchronization (m)	Establish E2E connection (Set comm. parameters)	Communicate with other TI nodes for control only	TI nodes (Edge and core)
Haptic Synchronization (m)	Establish E2E haptic-specific parameters (session, codecs, etc)	Communicate with other TI nodes for control only	TI nodes (Edge and core)
Operation (m)	Carry out normal TI operation	Communicate with other TI nodes for data only	TI nodes (Edge and core)
Recovery (network) (m)	Recover from network failure	Communicate with other TI nodes for control only	TI nodes (Edge and core)
Recovery (operational) (m)	Recover from operational error or data/encoding errors	Communicate with other TI nodes for control only	TI nodes (Edge and core)
The operator takes control (m)	Operate manually the UAV	Communicate with other TI nodes for control only	TI nodes (Edge and core)
Termination (m)	Terminate connection	Tear down connection with TI Edge & TI Core	TI nodes (Edge, core, local parent)

4

Implementation of Fire-Fighting TI Drones

4.1 Use case scenario and parameters

The plurality of the applications that UAVs are being used makes them very different from each other. So that makes it very difficult to make general rules for them. Hence, we should mention that the indicators that could trigger the transition from autonomous flight to manual depend on a lot of factors. For instance, a commercial quad-rotor drone-like Mavic 2 Enterprise Series (Chinese commercial drone) [65] has very different specs than a fixed-wing UAV, like the Greek-made UAV DELAER-RX3 (a project of Aristotle University of Thessaloniki) [66].

4.1.1 Operational setup

4.1.1.1 Fixed Wing UAV

In a fixed-wing UAV what the thresholds in order for the operator to take control of the device could be the stall speed and the abrupt change of height. Stall speed is the speed at which a drone cannot anymore maintain control and should gain power. The abrupt change of height is a common situation for aerial vehicles which could happen from many factors. For instance, the microclimate, an engine failure, etc are some of them, in fixed-wing UAVs, we could admit that after 50 m/s the operator should take the control of the UAV. The sensors that could trigger the operation are installed into IMUs and more specifically is the gyroscope, the accelerometer which combined with the GPS/GNSS sensor will give the required information.

4.1.1.2 Rotor UAV

On the other hand, the rotor UAVs which are much more spread, because of the low cost, have other aerodynamic characteristics and the ability of hovering makes the stall speed a factor without importance. Apparently, Tilt Angle and the abrupt change of height are the situations that we will focus on. Tilt Angle is the angle that beyond it the drone will lose its stability and the operator should obtain the control. An abrupt change of height is a violent loss or gain of height that makes the drone unstable.

The sensors that should trigger the operation are installed into IMUs and more specifically is the gyroscope, the accelerometer which is combined with the Tilt sensor, and the GPS/GNSS sensor will give the required information.

4.2 DELAER-RX3

DELAER-RX3 Figure 35 is a research project of Aristotle University of Thessaloniki [67], the main goal of the project was the development of a prototype fixed-wing unmanned aerial system (UAS), which could provide, direct support to Greek isolated territories and islands, via aerial delivery of lifesaving supplies and dedicated equipment. Apparently, the payload and the time flight play a vital role in this project in order for the UAS to be able to deliver the needed goods to every corner of Greek territory. In our use case, we’ve decided to use the DELAER-RX3, as a role model to clarify the circumstances, in which it is possible to switch from autonomous to manual flight. Although the main goal of DELAER-RX3 is to support Greek isolated territories and islands, via aerial delivery of lifesaving supplies and dedicated equipment, we will handle the UAS as an aerial platform of sensors. The main sensors that we could install to the UAS are a gyroscope, an accelerometer, and a GPS/GNSS which in close cooperation with IMU would provide the flight data to the operator.

Figure 35 The Prototype DELAER RX-3 [66]

The specifications of the prototype are analyzed in Table 8.

Table 8 Specifications of DELAER UAS

GTOW [kg]	190
Fuel weight [kg]	40
Cargo weight [kg]	40
Wingspan[m]	7.15
Λ[deg]	35
AR [-]	8

λ [-]	0.5
Endurance[h]	2
Maximum speed[km/h]	210
Stall speed [km/h]	79
Rate of climb[ft/m]	700
Take off runway [m]	136

4.2.1 Operation

During the delivery of goods, the DELAER RX-3 makes a maneuver Figure 36 that resembles a bomber that is sinking during airstrike operations. At this specific maneuver, the aircraft-UAV is sinking to the target and it’s leaving its load, above the target, subsequently, UAV gains its immediate height by applying rotary maneuvers, to reduce the elevation angle. A similar procedure is applying also during wildfire extinguishing. The drone should fly very close to the ground to leave its target above the fire, this is a very demanding procedure, because of the micro-climate that is created in wildfires.

Specifically, the thermal columns that are being created during a wildfire make drones change their aerodynamic behavior, so when the drone sensors receive data that are close to losing the aerodynamic stability Table 8, Table 9 the autonomous flight should stop and the operator takes control, also we have to keep in mind that the operator should receive haptic feedback that could be transmitted by the form of vibration on the controls, a hydraulic chair or an exoskeleton [68].

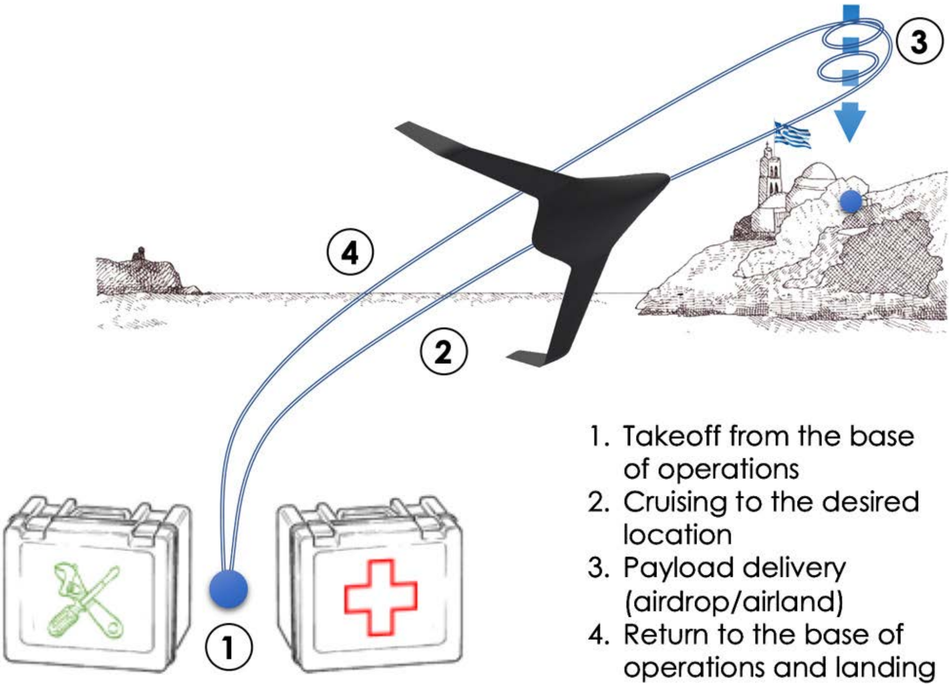

Figure 36 DELAER UAV mission profile [67]

Table 9 Aerodynamic limits for UAVs Accordingly Type

Type of Drone	Max Tilt Angle	Stall speed
DELAER RX-3	-	79 km/h
Mavic 2 Enterprise Series	35° (S-mode, with remote controller) 25° (P-mode)	-

4.3 Message exchanges and operational states

4.3.1 The ASN.1

ASN.1 has been in use since 1984 but has been constantly upgraded to meet new demands. In 1988 it was improved to support X.509 digital certificates, in 1995 it was improved to support the bandwidth and CPU-constrained devices, and in 2002 it was improved to support XML. ASN.1 is today used in a wide range of applications and is deployed in well over a billion computers and embedded systems devices [69].

4.3.1.1 Definition

ASN.1 is a formal notation used for describing data transmitted by telecommunications protocols, regardless of language implementation and physical representation of these data, whatever the application, whether complex or very simple [69], [70], [71], [72, p. 1].

4.3.1.2 ASN.1 Specifications

The specifications of ASN.1 are analyzed as follows:

- It is an internationally standardized, vendor-independent, platform-independent, and language-independent notation for specifying data structures at a high level of abstraction.
- It is supported by rules which determine the precise bit patterns, using encodings.
- It is supported by tools available for most platforms and several programming languages.
- It provides support for, interworking between previous versions.
- It provides interoperability by one standards group, with other standards groups developing.

4.3.2 Message exchanges

In the sub-chapter follows we provide the ASN.1 messages that are being exchanged between sensors (S) and GN (Figure 34,Table 7).

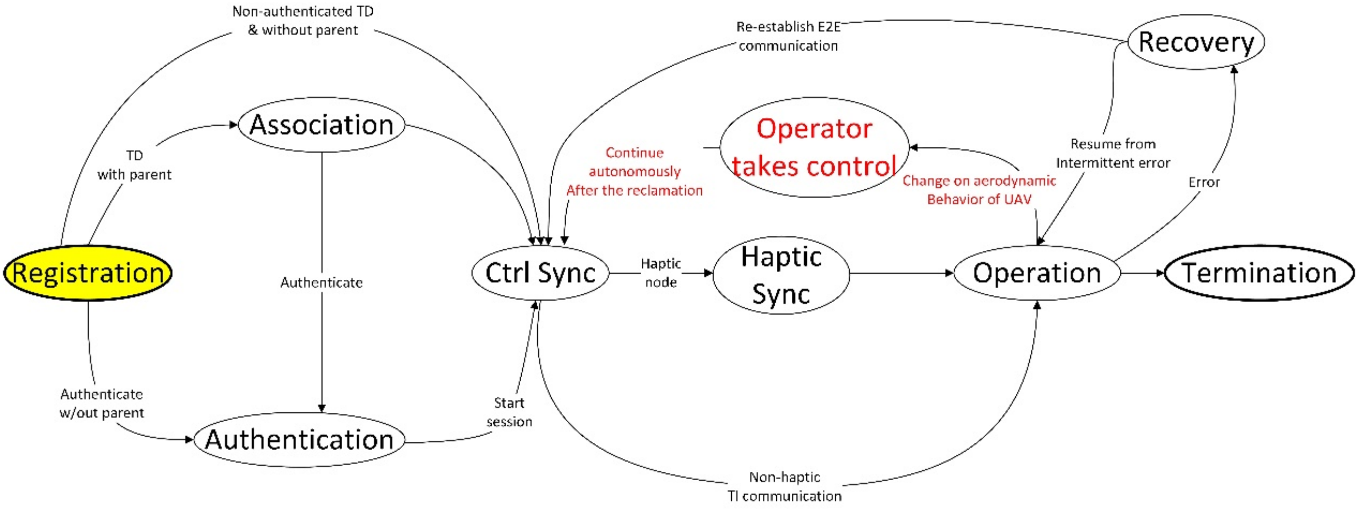

Figure 37 Registration State based on [3].

1. State: Registration, TI-node (TE) to TSM communication (Figure 37). [Loosely following the currently existing Kerberos protocol – slightly simplified [73].]

TIMessage::=SEQUENCE {
currentMode **Mode**,
pduLayer **Stack**,
sourceAddr **Addr1**,
destAddr **Addr2**,
sourceType Node1,
destType Node2,
header “TicketGranting”,
payload **KDC-Request**
}

Mode::=SEQUENCE {
opParams **Params,**
state **State,**
cotrollerAddr **Addr3,**
controllerType **Pnode**}

State::=SEQUENCE {
stateCode 1,
stateName “registration”}

The parameters are selected based on the common parameters during authentication messages following the Kerberos Authentication Protocol.

Addr1::=SEQUENCE {
port 50125,
netAddr 123.134.201.234}

Addr2::=SEQUENCE {
port 62324,
netAddr 234.167.528.671}

Etc. for all other addresses
Node1::=SEQUENCE {
typeID 3,
typeName “TSM”}

Node2::=SEQUENCE {
typeID 12,
typeName “SN”}

*/We select to show the communication between a sensor node (network interface for a sensor and the TSM that provides the authentication for successful registration of the node).

PNode::=SEQUENCE {
typeID 2,
typeName “GN”}

*/In bold letters are the contents described in accessory messages, below. The GN controls everything exiting the Tactile Edge. The ANs, SNs, etc. do not in general ‘talk’ directly to the TSM.

Stack::=SEQUENCE {
layerID 1,
stackType “TCP/IP”}

KDC-Request::=SEQUENCE {
protocolVersNo 5,
msg-type 2,
request-body **KDC-Request-Body**}

KDC-Request-Body::=SEQUENCE {
KDC-Options **Params**,
ClientName **PrincipalName1**,
Realm “DroneFireFigthing”,
ServerName **PrincipalName2**,
From 12:34:34.45, /* Time format will be different */

Till 07:34:34.5,
Nonce 1,

Etype 2234, /* Encryption type, an enumeration */
Encr-Author-Data **EncryptedData**}

Params::=SEQUENCE { /* Alternatively: BIT STRING */
reserved TRUE,
forwardable TRUE,
proxiable FALSE,
proxy FALSE,
allow-postdate FALSE,
postdate FALSE,
renewable TRUE,
enc-tkt-in-skey TRUE,
renew TRUE,
validate TRUE}

PrincipalName1::=SEQUENCE {
Name-type 3,
Name-String “IMU3”,}

PrincipalName2::=SEQUENCE {
Name-type 10,
Name-String “TSMserverforthisregion”,}

EncryptedData::=SEQUENCE {
Etype 2234,
KerbVersNo 5,
Cipher /* A string (octet containing the cipher) */
Ticket **Ticket**}

Ticket:: SEQUENCE{
Tkt-Version 5,
Realm **Realm**,
ServerName **PrincipalName2**,
Enc-Part **EncryptedData}**

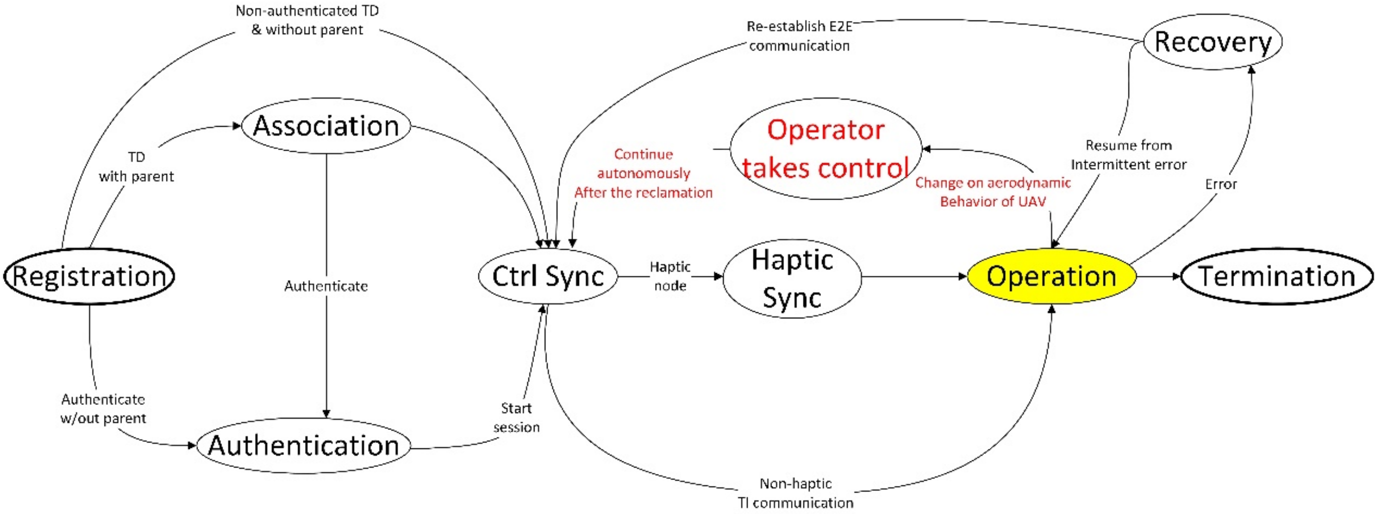

Figure 38 Operation State based on [3].

2. State: Operation, TI-node (TE) to TI-node communication (Figure 38). (Autonomous Flight)
TIMessage::=SEQUENCE {
currentMode **Mode,**
pduLayer **Stack,**
sourceAddr **Addr1,**
destAddr **Addr2,**
sourceType Node1,
destType Node2,
header “AutonomousFlight”,
payload **IMUData**
}

*/Inertial Measurement Unit (IMU) is, in particular, a microcomputer that checks and transmit all the needed values from sensors that are installed into the UAV

Mode::=SEQUENCE {
opParams **Params,**
state **State,**
Compensation FALSE**,**
cotrollerAddr **Addr3,**
controllerType **Pnode**}
State::=SEQUENCE {
stateCode 6,
stateName “operation”}

Params::=SEQUENCE {
maxLatency 10.0,
minReli 99.9999
minAvail 99.9999
minCapacity 130000}

Node1::=SEQUENCE {
typeID 3,
typeName “TSM”}

Node2::=SEQUENCE {

typeID 12,
typeName “SN”}

*/In this stage of the state machine the operator is just an “observer” that watches if the drone follows the pre-agreed path.

*/Etc. for all other addresses

PNode::=SEQUENCE {
typeID 2,
typeName “GN”}

The GN controls everything exiting the Tactile Edge

Stack::=SEQUENCE {
layerID 1,
stackType “TCP/IP”}

IMUData ::=SEQUENCE{
Longitude REAL,
Latitude REAL,
Altitube REAL,
Tilt Angle REAL,
Accelaration REAL}

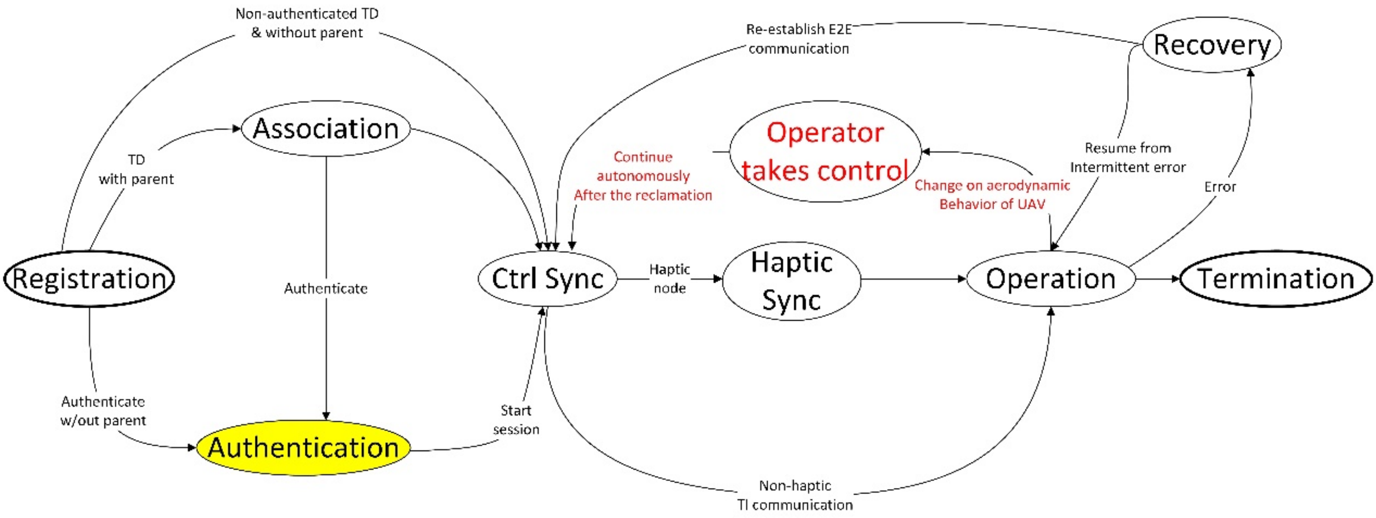

Figure 39 Authentication State based on [3].

3. State: Authentication (Figure 39)
TIMessage::=SEQUENCE {
currentMode **Mode,**
pduLayer **Stack,**
sourceAddr **Addr1,**
destAddr **Addr2,**
sourceType Node1,
destType Node2,
header “3wayAuthentication”,
payload **Credentials**
}

Mode::=SEQUENCE {
opParams **Params,**
state **State,**
cotrollerAddr **Addr3,**
controllerType **Pnode**}

State::=SEQUENCE {
stateCode 2,
stateName “Auth”}

Addr1::=SEQUENCE {
port 50423,
netAddr 124.434.401.264}
Etc. for all other addresses

Node1::=SEQUENCE {
typeID 8,
typeName “TD”}

Node2::=SEQUENCE {
typeID 3,
typeName “TSM”}
The messages use the TSM to successfully authenticate the TD on the operator’s side.

PNode::=SEQUENCE {
typeID 2,
typeName “GN”}
The GN controls everything exiting the Tactile Edge

Stack::=SEQUENCE {
layerID 1,
stackType “TCP/IP”}

Credentials::=SEQUENCE{
Username “Operator”,
Password XXXXX,
Biometrics “fingerprint”}

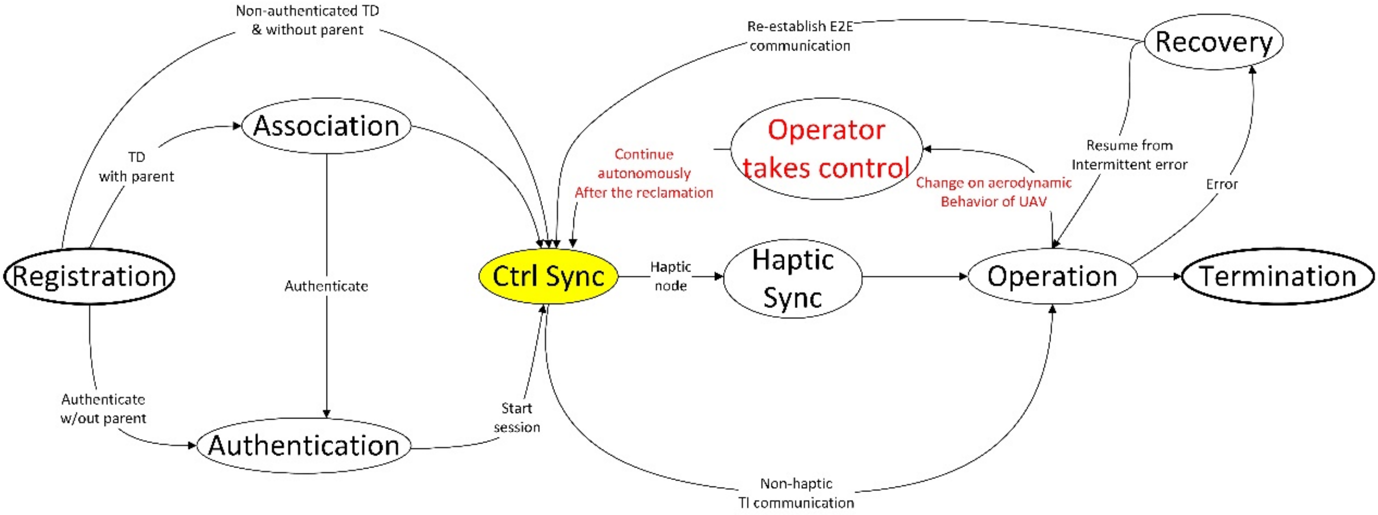

Figure 40 Control Synchronization State based on [3].

4. State: Control Synchronization between GNC and some CPE in the network domain (Figure 40). [Part of state: Haptic Parameters Synchronization]
TIMessage::=SEQUENCE {
currentMode **Mode,**
pduLayer **Stack,**
sourceAddr **Addr1,**
destAddr **Addr2,**
sourceType Node1,
destType Node2,
header “HapticParametersSync”,
payload **QoSParams**
}

Mode::=SEQUENCE {
opParams **Params,**
state **State,**
cotrollerAddr **Addr3,**
controllerType **Pnode**}

State::=SEQUENCE {

stateCode 4,
stateName “Cntrl_Sync”}

Addr1::=SEQUENCE {
port 50125,
netAddr 123.134.201.234}
Etc. for all other addresses

Node1::=SEQUENCE {
typeID 6,
typeName “GN”}

Node2::=SEQUENCE {
typeID 1,
typeName “CPE”}

The messages try to establish that there is enough bandwidth to support the required QoS for a successful operation. It communicates with a network-based CPE to demand bandwidth for all aspects of QoS.

PNode::=SEQUENCE {
typeID 2,
typeName “GN”}
The GN controls everything exiting the Tactile Edge

Stack::=SEQUENCE {
layerID 1,
stackType “TCP/IP”}

QoSParams:: SEQUENCE{
haptfeedreq **HapReqs**}

HapReqs::= SEQUENCE{
ForceLatency 5,
ForceJitter 1,
ForceDataRate 130
VibrationLatency 5.5,
VibrationJitter 1,
VibrationDataRate 130}

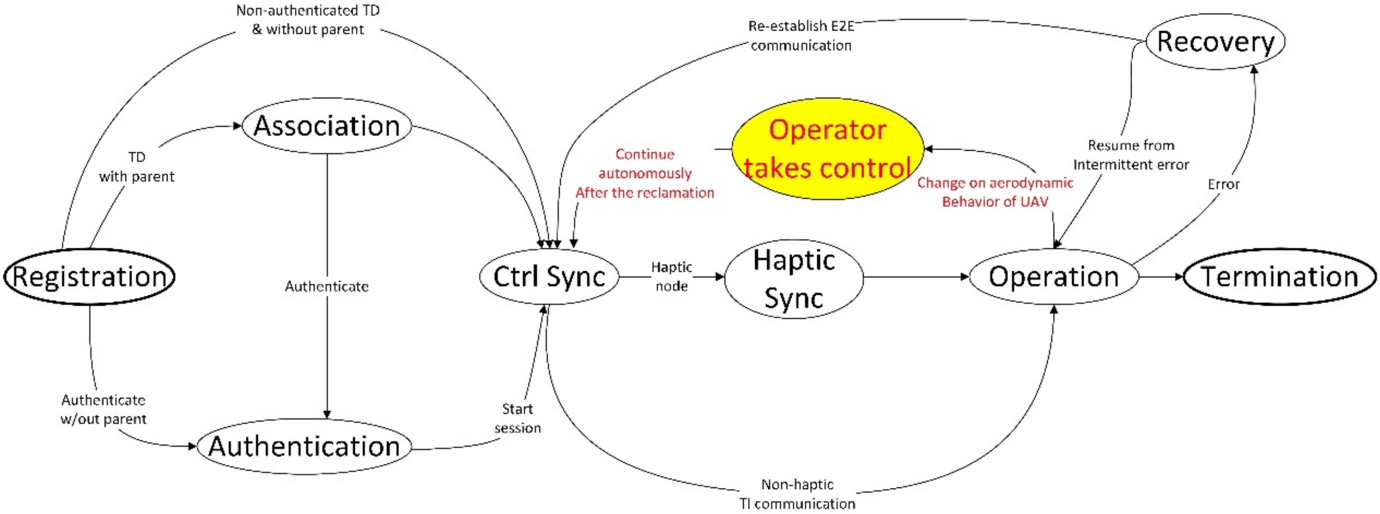

Figure 41 Operator Takes Control State based on [3].

5. State: Operator takes control after changing of aerodynamic behavior of the UAV (Figure 41)

TIMessage::=SEQUENCE {
currentMode **Mode,**
pduLayer **Stack,**
sourceAddr **Addr1,**
destAddr **Addr2,**
sourceType Node1,
destType Node2,
header “OperatorTakesControl”,
payload **DATA**
}

Mode::=SEQUENCE {
opParams **Params,**
state **State,**
Compensation FALSE**,**
cotrollerAddr **Addr3,**
controllerType **Pnode**}
State::=SEQUENCE {
stateCode 9,
stateName “operatortakescontrol”}

Params::=SEQUENCE {
maxLatency 5.0,
minReli 99.9999
minAvail 99.9999
minCapacity 130000}

Addr1::=SEQUENCE {
port 50125,
netAddr 123.134.201.234}

Addr2::=SEQUENCE {

port 50124,
netAddr 127.334.324.168}
Etc. for all other addresses

Node1::=SEQUENCE {
typeID 14,
typeName “S”}

Node2::=SEQUENCE {
typeID 13,
typeName “A”} */The actuator would be the vibrator motor on the operator steering wheel or a hydraulic system that could change the tense of reaction according to the intensity of aerodynamic alteration of the UAV.

PNode::=SEQUENCE {
typeID 2,
typeName “GN”}

The GN controls everything exiting the Tactile Edge

Stack::=SEQUENCE {
layerID 1,
stackType “TCP/IP”}

5 Conclusions & Future work

5.1 Concluding remarks

TI will play an important role not only in the relevant scientific fields but also in the daily lives of ordinary people. Its applications, which have already begun to be studied by the international scientific community, but also those that will emerge, are directly related to the daily lives of people. This is the reason why we have been seeing intense scientific activity in recent years from the scientific community.

In this dissertation, we tried to outline the specific features of TI and its areas of application, like healthcare, IoD, industry, etc. We also placed special emphasis on the scientific challenges, like latency, reliability and security, and technologies on which TI should rely in order to be implemented as close as possible to its vision. In addition, we referred to the 5G technology which in the coming years will dominate the wireless-cellular networks and its technologies like mmWave, massive MIMO, extremely small cells, ultra-dense networks, and heterogeneous networks, and the slicing network.

In addition, we referred to drones in general, as well as how they can be used in disasters in general and in a forest fire particularly. We also highlighted the specifics of such a fire in order for the reader to realize the demanding environment that fire-fighting drones will act, and presented a proposed architecture, which would help address the problem of the particular microclimate that prevails during such a fire, and the changing of the aerodynamic behavior of the drone that could induce, always respecting the principles of TI. Moreover, it has been proven by many incidents in aviation history that a well-trained operator could overcome situations in which the volatile medium, comes into a loss of stability situation much better than an automated pilot. Especially for the development of the above-mentioned architecture, we relied on the previous work which was carried out by the IEEE P1918.1 TI WG which provided us through [3] with the necessary tools for the design of the above architecture.

Based on the IEEE P1918.1 TI WG work, this Thesis tries to describe an example of how a given use case can be implemented. For the implementation we are using the DELAER RX-3, which is an Aristotele University of Thessaloniki, project which has a similar role to our fire-fighting drone, to deliver goods to remote locations in Hellenic territory. Moreover, we provide details about a specific scenario of dropping firefighting balls to a wildfire. The firefighting drones have been chosen as it is a typical scenario that falls in the vast category of the teleoperation use cases. Moreover, examples of TI messages exchanged during the operating of a firefighter drone that acts over the demanding environment of a wildfire, sessions are demonstrated.

5.2 Future work

TI will find novel application fields in which to contribute to the solution of the complex challenges faced by our society. In accordance with TI vision, human senses can interact with machines, and technology's potential in this respect is growing. The Tactile Internet will enable haptic interaction with visual feedback, with technical systems supporting not just audiovisual interaction, but also that involving robotic systems to be controlled with an imperceptible time-lag. The further development of haptic devices will provide the necessary tools for the implementation of TI applications.

Moreover, we should mention that TI in its final form should provide haptic information in distances a lot bigger than 150 km, and at the same time, E2E delay should stay under 1 ms especially for the time-critical applications. So novel task scheduling algorithms are necessary as the location of the task execution can affect the E2E delay.

Furthermore, another factor that needs further improvement is the coverage of cellular networks and especially 5G. Indeed, according to [74], the coverage of the 5g network needs to be expanded, and if we want use cases such us, fire-extinguish by drones in wildfires, to be a reality the expanding of the above-mentioned networks deemed necessary.

Another area in which there should be a significant improvement is the development and improvement of specialized algorithms and artificial intelligence (AI) practices that will help implement TI applications, always respecting the specific requirements of TI and especially that of a delay of less than 1ms, for E2E communication. The further improvement of AI algorithms will predict actions that could help the implementation of our use case. AI engines are used to predict the haptic experience (movements, reactions) and that is possible because our actions are mainly repetitious and follow particular patterns. To achieve the implementation of AI techniques fog and cloud technologies could be used in order to fulfill the latency requirements and improve the QoE of TI users. The IEEE P1918.1 TI WG has acknowledged its importance and discussions are made whether a future potential additional standard or amendment might be developed.

In addition, the further growth of haptic codecs will aid the integration of TI vision. The first step was held by IEEE P1918.1 TI WG in [3], but further improvement and the integration of new technics in order to create efficient haptic codecs should be implemented for sure.

Finally, the practical implementation of new use cases will give us, concrete and useful data and will provide innovative services and applications. Support for TI use cases in the healthcare, the automotive, the IoD, the entertainment industry, and the education demands for connectivity and network solutions, standardization efforts, and strong partnerships. As a result, opportunities for new strong markets will appear for the telecom companies which will invest in the new sector.

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