Ontology based framework for Tactile Internet and Digital Twin Applications

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Abstract

In the era of Industry 4 and Digital Twin – DT- (integrating Audio-Video, Virtual Reality, Augmented Reality and Haptics - from the Greek word Haptikos meaning "able to touch") and the Tactile Internet (TI), it becomes obvious that telecom stakeholders need different networks requirements to provision high quality services with respect to the new standards. In reality, this era is proposed as TI, and it will achieve a true paradigm shift from content delivery to skill-set delivery network types, thanks to recent technical breakthroughs. It will build a new internet structure with improved capabilities; but it will be difficult to meet the technical needs of the TI with current fourth generation (4G) mobile communication systems. As a result, 5G mobile communication systems will be used at the wireless edge and as a key enabler for TI due to its automated core network functionalities.

Because of the COVID-19 outbreak, most daily activities such as employment, research, and education are now conducted online rather than in person. As a result, internet traffic has risen dramatically. Nowadays, Tactile Internet is in its infancy deployment phase worldwide. For this reason, and because of the growing need of its applications, the feasibility of these applications on the existing and deployed networks infrastructures, especially in the growing countries, is thought to be very hard, even quasi-impossible. Since 5G is not reaching yet its convergence stage (i.e. it is not deployed everywhere) and there is a huge stress on mobile communications given that the world is still facing the COVID-19 Pandemic, and since all the activities are taking place online, we propose design and implement a QoS framework to facilitate the feasibility and the applicability of the TI systems, where no 5G infrastructure is deployed. This framework will predict the most suitable network type to be deployed for certain given TI applications with certain given KPIs (Key Performance Indicators). Also, this framework is scalable, in such it gives an idea of even the future Next Generation Mobile Networks types (NGMN, if necessary).

“To deal” with TI applications, means “to deal” with Haptics added to Audio and Video streams. Therefore, performance evaluation for haptic networks is required. And since there are different types of haptic networks, so interoperability is needed. Consequently, a standardization form is necessary for that purpose, to annotate and describe the haptic network. The first idea that flashes in mind, is the use of Ontologies. In these latters, we can add intelligent rules to infer additional data and predict resource requirements in order to achieve better performance. Many works in the research rely on Artificial Intelligence approaches to tackle the above-mentioned standardization, but very few depend on ontologies, and without futuristic outcomes, especially for the optimization problem. We mean by optimization, the optimal types, methods and rules that are able to accommodate the applicability of the TI systems (here come the applications KPIs) in an acceptable environment or infrastructure (here come the networking KPIs), and even-more, to infer the most optimal network type.

To help manufacturing companies take full advantage of the TI, we propose to develop new methods and tools (ontologies) to intelligently handle the TI, DT (Digital Twin) and IoT (Internet of Things) sensor data and process data at the edge of the network and deliver faster insights. The outcomes of these ontologies, have been validated through two conducted case studies, where we simulated, in the first, TI traffic over Wi-Fi, WiMAX and UMTS (3G) infrastructures; While in the second we used 4G (LTE-A), along with SDN (Software Defined Networking) integrated to MEC (Mobile Edge Computing) as networking backbone. The results, in terms of QoS KPIs performance evaluation, present high relevance to our proposed Ontology outcomes.

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Finally, I am happy to have a great and a wonderful mother in my life, guiding me through all the trials and tribulations of this road.

Dedicated to the soul of my Father
May Allah rest his soul in heaven

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List of Abbreviations

3D: Three-Dimensional

3G: The third generation of broadband cellular network technology

3GPP: 3rd Generation Partnership Project

4G: The fourth generation of broadband cellular network technology

5G: The fifth generation technology standard for broadband cellular networks

AI: Artificial Intelligence

AMPS: Advanced Mobile Phone System

ANS: Autonomic Nervous System

API: Application Programmable Interface

AR: Augmented Reality

AV: Audiovisual

BER: Bit Error Rate

CAHVE: Collaborated Haptic Virtual Environment

CAPEX: CAPital EXpenditure

CDN: Content Delivery Network

CPS: Cyber Physical System

D2D: Device-to-Device

DiffServ: Differentiated Services

DL: DownLink

DT: Digital Twin

DoF: Degree of Freedom

DOLCE: Descriptive Ontology for Linguistic and Cognitive Engineering

DUL: Dolce Ultra Lite

E2E: End-to-End

NB: evolved NodeB

EPC: Evolved Packet core

FDD: Frequency Division Duplex FIS: Fuzzy Information System FSM: Finite State Machine
Gbps: Gigabit per second

GPRS: General Packet Radio Service

GSM: Global System for Mobile communications

H2M: Human to Machine

HAVE: Haptic-Audio-Visual Environments

HD: High Definition

HRV: Heart Rate Variability

HVR: Haptic Virtual Reality

HCI: Human-Computer Interaction

ICT: Information and Communications Technology

IEEE: Institute of Electrical and Electronics Engineers IIoT: Industrial IoT

IMT: International Mobile Communications

IntServ: Integrated Services

IoT: Internet of things

IP: Internet Protocol

ITS: Intelligent transport Systems

KPI: Key Performance Indicator

LTE-A: Long-Term Evolution-Advanced

M2M: Machine-to-Machine MBB: Mobile BroadBand

Mbps: Megabit per second

MDF: Median Frequency

MEC: Mobile Edge Computing

MIMO: Multiple Input Multiple Output

MMC: Massive Machine Communication MMT: Model-Mediated Teleoperation

MNF: Mean Frequency

MPLS: MultiProtocol Label Switching

MVS: Multi-View Stereo

MR: Mixed Reality

NFV: Network Function Virtualization

NGMN: Next Generation Mobile Network

OF: OpenFlow

OPEX: OPerational EXpenditure

OWL: Web Ontology Language

PNS: Peripheral Nervous System

PD: Perceptual Dead band

QoE: Quality-of-Experience

QoS: Quality-of-Service

RAN: Radio Access Network

RDF: Resource Description Framework

RF: Radio Frequency

RSVP: Resource Reservation Protocol

RTT: Round Trip Time

SDN: Software-defined Networking

SDNC: SDN Controller

SDP: Session Description Protocol

SITL: System In the Loop

SOAP: Simple Object Access Protocol

SON: Self-Organizing Network

SUMO: Suggested Upper Merged Ontology

Tbps: Terabit per second

TCP: Transmission Control Protocol

TDPA: Time Domain Passivity Approach

TI: Tactile Internet

UE: User Equipment

UL: UpLink

UMTS: Universal Mobile Telecommunication System (same as 3G)

UX: User Experience

VoIP: Voice over Internet Protocol

VR: Virtual-Reality

VE: Virtual Environments

Wi-Fi: Wireless Fidelity

WiMAX: Worldwide Interoperability for Microwave Access (WiMAX)

Chapter 1 - Introduction

Communication latency has been a dominant issue for the most networking applications in late years. A number of communication standards and protocols have been developed to address this problem. However, even after these developments, network latency problem persists, keeping in mind the quality of service (QoS) and experience quality (QoE) for different applications. To deal with the issues described above, this thesis surveys issues and challenges related to the development of this type of delay-sensitive applications, like tactile Internet and Digital Twin, and proposed a framework (ontology) that uses Tactile Internet in the core for delay mitigation using different wireless networks (Wi-Fi, WiMAX, 3G, 4G, and 5G), as backbones, for future ultra-reliable and low-latency applications. These include Healthcare 4.0, Industry 4.0, Digital Twin, Virtual/Augmented Reality, smart education, and smart transportation.

In the present world of technology, virtual objects are becoming increasingly common. Tactile internet is a system that allows users to interact with virtual objects as if they were real objects. This type of Internet is expected to have a maximum latency of 1 millisecond in order to provide a realistic experience.

Perhaps, the most prominent application of Tactile Internet, is the Digital Twin. El Saddik [1] developed the concept of a digital twin as a digital reproduction of a live or non-living physical thing. Data is seamlessly conveyed via linking the physical and virtual worlds, allowing the virtual entity to coexist with the actual entity. A digital twin is an ambient multimedia that embellishes the "scooters" for monitoring, understanding, and optimizing the functions of a physical entity while also providing constant feedback to promote quality of life and well-being. It is the fusion of numerous technologies, including Artificial Intelligence (AI), Mixed Reality (MR) and Haptics, the Internet of Things (IoT), cyber security, industry 4.0, and health 4.0.

1.1 - Motivations

Mobile communication has allowed users to exchange data using smart devices, no matter where they are, and thus through utilizing Mobile Internet (MI). Users can connect to the internet through their smart mobile devices, which are connected to millions of other devices. This has changed industries such as education, logistics, health care, transportation, and gaming by preserving quality of service and quality of experience while allowing device-to- device communication. A D2D communication system is a type of wireless communication that provides direct device-to-device (D2D) communication, where the mobile devices communicate directly with each other without any need for an access point. This kind of system paved the way to what is called the Internet of Things (IoT) [2]. In 2013, IBM coined the term "Internet of Things" (IoT): a network of physical instruments, home appliances, vehicles, and other elements installed with software, electronics, sensors and networking infrastructure to let these things communicate and transfer data. Applications include smart cities applications (like smart parking, smart lightening, traffic congestion, forest fire detection, and waste management), industrial automation and logistics. D2D communications are used in pairs of devices that are located relatively close to each other and share prime or critical information with each other. Such information can be exchanged in real time, in a way that, even a delay of millisecond, can hurt people's life (for example transferring a robotic telesurgery data). For instance, existing cellular networks are not relevant for such sensitive data exchange due to slow data throughput and a considerable latency (greater than 20 ms). However, for D2D communications, this delay is unacceptable for most of the smart applications. The Figure 1.1 shows the different technological trends for Tactile Internet.

Traditional networks (like the 4G-LTE with latency ≈ 20 ms) are not responsive enough for remote robotic operations that require quick responses, such as tele-surgery, tele-rehabilitation, and smart traffic control.

The foundation for the rise of Tactile Internet has already been decided: 5G networks offer ultra-active and ultra-stable data transmission, with a round-trip delay of less than 1 millisecond [2, 3]. They can also transmit, remotely, physical perceptions and real-time controls employing haptic communication. Haptic communication is the use of devices that are intended for human tactile perception, like braille terminals and graphics tablets.

It includes kinesthetic feedback (like force feedback, speed, torque, position, and displacement of objects) or tactile feedback (like a vibration, texture of surface, and friction percentage) [4]. It may also include non-haptic data, like speech or video. Haptic communication is used in a variety of settings, including gaming and education.

Delivery networks have changed over time. In the past, they were known as content- delivery networks. Today, delivery networks are called skill-set delivery networks because they deliver information instead of data [5]. For example, legacy wired or wireless networks carry voice data, video streaming, text messages, and emails through their content delivery nodes (CDN). But the skill-set delivery networks are developed to transport physical touch experience (or skill) adopting haptic tools, that is, the future internet will make it possible to touch and feel objects using a computer. It will be able to sense pressure, temperature, and pain, expressly the future Tactile Internet [2, 10].

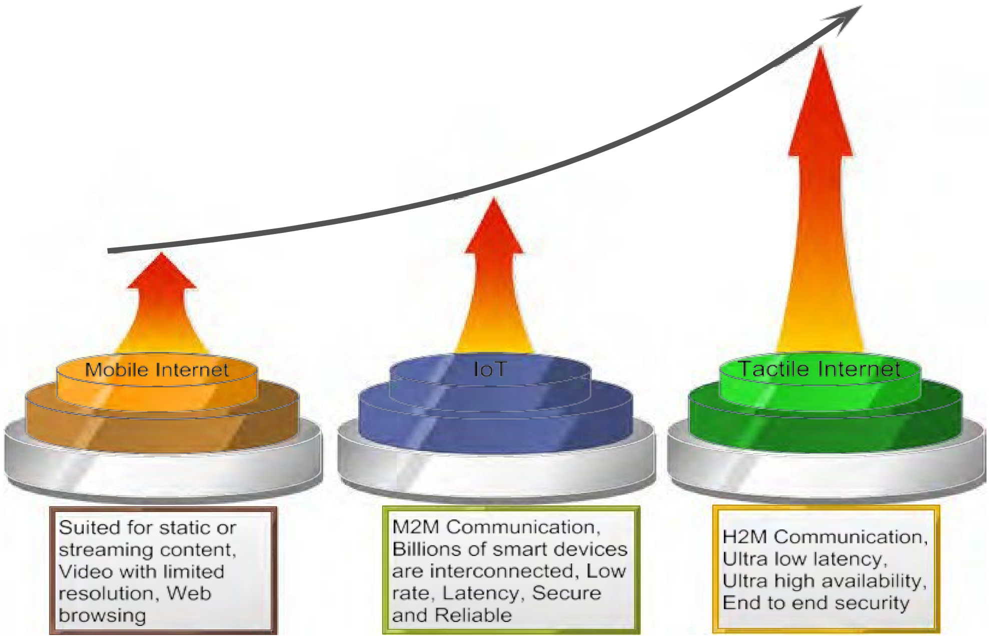


Figure 1.1: An examination of technical trends in comparison

With designs driven to near perfection, the Internet age was thought to be the last, but the never-ending journey of discoveries and research forced humanity to adopt the new era. Today, with the evolution of the Internet of Things (IoT), a thousand billion connected things will define a new mobile network generation. Meeting the specifications of the Tactile Internet, is a major part of the current studies on the fifth generation of mobile networks (5G) [5, 149]. Tactile Internet will allow for real-time communication of human touch and actuation. It will provide an essential pattern change from content-distribution networks to skill set/labor distribution networks allowing the realization of a new class of Cyber Physical Systems referred to as the Digital Twin. A Digital Twin (DT) is a digital replica of a living or non-living physical entity. As a result, it refers to a digital reproduction of possible and current physical assets, processes, people, locations, systems, and equipments that can be used for a variety of reasons (physical twin). A digital twin trains and upgrades itself from many sources in real time to represent its status, operating condition, or location. Using sensor data that reflects many characteristics of its working condition, this learning system learns from itself [1]. Since it is filled with sensors, is connected to wireless networks, and shares data and communicates with other devices, the digital twin relies on Cloud platforms driven by Machine-to-Machine communications (M2M) and Data Analytics. The connectivity of digital twin technology is one of its most distinguishing features. Sensors on the physical object create this connectivity by collecting data and integrating and communicating it via various integration technologies. We can also create a digital twin of nearly anything, regardless of its scale, ranging from simple components and assets (rotors, turbines, pipelines, and so on) to complicated processes and ecosystems (production lines, manufacturing plants, wind farms, etc.). The digital twin models' level of complexity and detail is determined by the availability and maturity of the information technology infrastructure. For all the aforementioned, the success of Digital Twin technology is dependent on internet connectivity. Without the latter, Digital Twin technology would not exist. Hence, providing an ultra-fast, reliable and secure connectivity, is a key condition for the realization of Digital Twin applications. Here comes the role of Tactile Internet (TI).

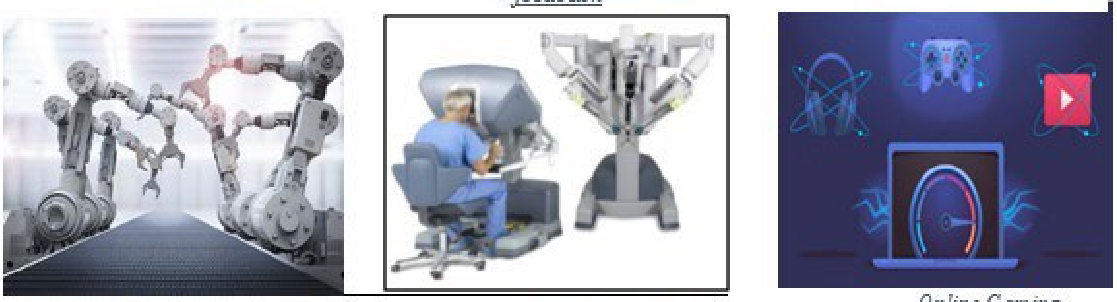
In addition, the key aspect of the Digital Twin's is the usage of multi-modal digital tools to bridge the gap between the physical and virtual worlds, with haptic added to 3D, audiovisual and mixed reality (MR) communication platforms. The Digital Twin is a concept, not a single product or piece of technology that combines numerous technologies — 3D simulation, IoT, 4G/5G, big data, blockchain, edge computing, cloud computing, and artificial intelligence — to bring the concept to life. Consequently, different applications will be offered by the Tactile Internet such as remote well-being monitoring and surgery (Health 4.0), remote driving, remote education and training, wireless commanded exoskeletons, industrial remote maintenance, and manufacturing (Industry's 4.0) [57].

Since most of the previous applications are critical to society, the Tactile Internet must be ultra-reliable and have an enough bandwidth to enable numerous devices to communicate at the same time. Moreover, it has to keep end-to-end latencies to the minimum, similar to the requirements of the 5G (i.e. 1 ms). In addition, the conveying of haptic information, in particular, places significant demands on the communication network because it closes a global control loop between the human (master) and the remote robot (slave). As a consequence, the system's stability is extremely vulnerable to network latency. Furthermore, high-fidelity teleoperation necessitates a high-level sampling rate for haptic signals of 1 kHz or greater in order to guarantee high-quality interaction and the stability of the system as a result, teleoperation systems necessitate the exchange of 1000 or even more data packets per second (PPS) among the master and slave devices. Such high packet rates are difficult to sustain in Internet-based networking [5, 149, 150, and 151]. This is, indeed, the main technical aspect of the challenge of the Tactile Internet. One suggested solution to tackle the low latency specification is to engage Software Defined Networking (SDN) and Network Function Virtualization (NFV) technologies in the existing network infrastructure (before the deployment of the 5G network) [10, 58]. Data centers, campus networks, and private networks were among the early adopters of SDN technology. This approach brings a potent and a very economical network design by physically separating the data forwarding plane from the control plane. The latter is the network segment defined by SDN controllers that grant the adequate selection to organize traffic. The data plane is the other segment characterized by pure, or hybrid switches, that lead the traffic upon control plane response. This splitting allows the utilization of open protocols (e.g. OpenFlow) to ensure communication between these different planes. SDN architecture empowers network to associate with applications through application programming interfaces (APIs), supporting application execution and security.

In addition, SDN makes a flexible and adaptable network design that can be configured remotely, enabling the third-party feature. Several studies highlight the advantage of integrating SDN with edge computing for traditional network and/or multimedia communication [152, 153]. However, this solution was not investigated and implemented in the literature to empower the realization of the Digital Twin.

IoT has already created many contingencies for smart home devices, but TI will be immersed on bringing more human-robot interactions [6].

Self-Driving Vehicles
AR and VR with haptic feedback
Efficient manufacturing



Industrial Automation
Tele-Medicine
Online Gaming

Figure 1.2: Modern tactile internet applications

In Tactile Internet systems, round trip delay should be less than 1 millisecond. An example of these systems is Augmented/Virtual Reality (AR/VR) systems, Cyber Physical Systems (CPS), and telepresence. There has been an increased interest in virtual reality (VR) and augmented reality (AR) technologies among the gaming industries. Yet, high-end interactive applications can be limited by a slow internet. TI may beat these constraints and build an extent for new low-latency highly bilateral and interactive gaming applications. Furthermore, ultra-reliability and ultra-low latency provided by TI, can serve various societal issues. Low latency is important for services that rely on quick response times, such as financial trading or remote surgery applications. Ultra-reliable systems are beneficial when the cost of failure is very high, such as in power plants, military systems or space exploration. Additionally, TI provides ultra-high end-to-end secure transmission and ultra-high availability.

Conforming to a study: Uncovering Real Mobile Data Usage and Customer Satisfaction, performed by The Boston Consulting Group (BCG) in late 2015, nearly 72% users are pleased with latencies ranging from 75 to 100 milliseconds. This percentage was lifted to 83% with latencies below 50 milliseconds [7]. As a matter of fact, the customer satisfaction level is reversed proportional to the network latency. Various generations of cellular networks have tried to decrease latency and increase user satisfaction. Few of these generations have become obsolete (1G and 2G) or about to become obsolete (3G) because of their high response time. On the other hand, 5G and TI will give the user ultra-reactive time, which is less than 1 millisecond.

The Tactile Internet will revolutionize the field of information and communication technology. Key examples of emerging Tactile Internet application fields are found in industry, augmented/virtual reality, remote healthcare, online gaming, robotics and telepresence, education and culture, smart grid, and road traffic. These applications are progressing towards precise human-to-machine and machine-to-machine interaction.

1.2 - Problem Statement

Due to the outbreak of COVID-19, the core of daily activities, including employment, education, and research, are now conducted online instead of personally. As a result, internet traffic has risen dramatically. According to recent estimates [8], internet traffic has increased by 70 percent to 300 percent since March 2020. Popular content providers such as Netflix and YouTube are slowing down across North America and Europe, according to a recent CNN news article[11], to prevent the internet from breaking. Even with the partial deployment of fifth generation mobile communication, the present network deployment and solutions are currently under a lot of strain. In the era of Industry 4.0 and Digital Twin (integrating Audio-Video, Virtual Reality, Augmented Reality and Haptics) and the Tactile Internet, it becomes obvious that telecom stakeholders need different networks requirements to provision high quality services with respect to the new

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[1] https://www.cnn.com/2020/03/19/tech/netflix-internet-overload-eu/index.html

standards. Anomaly detection, remote monitoring, control of processes and assets, and diagnosis, are just a few of the applications that have emerged in the manufacturing industry thanks to the capability of modern sensing technology. While significant progress has been achieved in recent years in making assets "smarter" and increasing production efficiency, the true strength of these new standards has yet to be fully realized.

But why the current networks cannot support tactile internet applications? Lot of requirements are need to be achieved in order to make Tactile Internet possible. The current networks don't have enough features in order to support haptic communications. The following are some weaknesses of current networks [2]:

1. Tactile Internet Twin systems require an ultra-low end-to-end latency, that is considerably less than the present applications and systems' end-to-end latency.
2. The manufacturing industry has extremely stringent data processing latency requirements.
3. It's difficult to guarantee connectivity (and thus service availability): Because of the requisite reliability and latency, current transmission protocols (e.g., UDP and TCP) cannot be used for tactile Internet applications, particularly for haptic based applications. As a result, new protocols should be developed.

How to fairly distribute the limited network resource that is made available to competing applications is a problem that plagues all such heterogeneous systems. A transcendental sense of how resources are distributed properly to end users is what we call: quality of service (QoS). In comparison to current networks, 5G is anticipated to carry 1,000 times more heterogeneous traffic, and it should perform up to 10 times faster than 4G/LTE. The 5G network's outstanding spectrum efficiency and exceptionally low end-to-end latency are further key features. This means that the 5G network must be completely aware of Quality of Service priority when transmitting high-speed information streams (such as audio/video packets) (QoS-aware).

The demand for self-optimizing, self-healing networks nowadays is driven by social media. The issues from the resulting massive volumes of data and their related computational complexities have proven intractable for traditional analytical QoS regulating approaches to resolve.

Among these advancements, semantically oriented computing demonstrates its capacity to handle the difficult issues of heterogeneity and interoperability presented by the abundance of objects with various features. In this regard, there is now a lot of research being conducted globally to discover creative 5G network QoS management/monitoring solutions using a future innovation enabler, the data-driven modeling, via ontologies.

Being the self-centered modality, Haptics performance evaluation is required. There are different types of haptic modalities, so interoperability is needed: A standardization form is necessary to annotate and describe, seamlessly and in a stable manner, the KPIs in existing networks. In ontologies, we can add intelligent rules to infer additional data and predict resource requirements in order to achieve better performance.

The primary challenge is figuring out how to achieve the service level agreement (SLA) with the amount of speed and granularity anticipated in a 5G network, as well as how to enhance subscriber connection experience. The end result of providing quality to the subscriber depends on the available bandwidth, including End2End delay, the consequences of bandwidth variation, and the likelihood of packet loss.

To deploy TI communications systems on existing network infrastructures, we can simulate scenarios in order to evaluate if we can meet the minimum network requirements for the Quality of Service KPIs such as E2E delay, Throughput, jitter, packet loss, etc.

And because of the non-static nature of these parameters, any modifications or changings of these parameters, will affect the Ontology, and therefore the rules and laws in it, making the ontology always up-to-date. By using these Ontologies, network operators and stakeholders will benefit from the standardization process, earning more revenues when provisioning Tactile Internet and Digital Twin applications.

Since 5G is not reaching yet its convergence stage (i.e. it is not deployed everywhere) and there is a huge stress on mobile communications given that the world is still facing the COVID- 19 Pandemic, and since all the activities are taking place online, we propose design and implement a QoS framework to facilitate the feasibility and the applicability of the TI systems, where no 5G infrastructure is deployed. This framework is developed with new tools, methods, and rules (ontologies) to intelligently handle the TI, DT and IoT (Internet of Things) sensor data and process data at the edge of the network and deliver faster insights. To help manufacturing companies take full advantage of the TI, we could demonstrate, through our proposed ontology platform that it is possible to benefit from TI applications on the current existing networks, with all the limitations and the weaknesses cited before. By integrating Mobile Edge Computing (MEC) and Software Defined Networking (SDN) with Network Function Virtualization (NFV) on an LTE-A network infrastructure, we managed to prove that 4G networks could handle TI applications, although, MEC, NFV and SDN are thought to be the most important key enablers for 5G networks [135] that can carry on TI applications. Moreover, we were able to validate the suitability – to a certain extent - of TI applications over tradition wireless networks Wi-Fi, WiMAX, and 3G.

1.3 - Contributions

In this section, we summarize our research contributions of this PhD work as follows:

- Designed and implemented a state-of-the-art ontology: Service Oriented Development of Haptics Ontology (SODHO) that integrates both sensors and actuators in a unified ontology, and constitutes the pillars that will shape the Haptic Interface System software design. It also serves as a blueprint for the design of tactile interfaces of Haptic Audio-Visual Environment (HAVE) used in future Tactile Internet and Digital Twin systems.
- We proposed a QoS KPIs Ontology for the 5G networks (KPION-5G), that relates the future 5G applications to their required network key performance indicators.
- Designed and implemented an ontology-based framework for Digital Twin and Tactile Internet applications (OFDTI), in which we imported the two previous ontologies in order to infer, along with an integrated Fuzzy Information System, the most suitable network type for a given TI application.

- Benchmarked existing mobile networks architectures, such as: Wi-Fi, WiMAX, and 3G, to investigate their suitability to carry on the applications of Tactile Internet applications, mainly: HAV Haptics, Audio (VoIP), and high resolution Video streaming.
- We proposed an architecture at which SDN, NFV (the modern network solutions) are incorporated with MEC to handle TI Communications over LTE-A. The results, in terms of QoS KPIs performance evaluation, present high relevance to our proposed OFDTI Ontology outcomes.

1.4 - Scholarly Articles

The research works compiled in this dissertation have been reported or will be reported in the following publications.

REFEREED JOURNAL PAPERS:

a) Mohammed Al Ja'afreh, **Hikmat Adhami**, Alaa Eddin Alchalabi, Mohamed Hoda and Abdulmotaleb El Saddik, "Toward Integrating Software Defined Networks with the Internet of Things: A review", *Springer Cluster Computing, 2021.*

b) **H.Adhami**, M. Alja'afreh, M. Hoda, J. Zhao, Y. Zhou, and A. El Saddik, "Suitability of SDN and MEC to Facilitate Digital Twin Communication over LTE-A", *(accepted).*

c) **H. Adhami**, M. Aljaafreh, and A. El Saddik, "Ontology based framework for Digital Twin and Tactile Internet Applications", *2022 (In process).*

BOOK CHAPTERS:

d) **Adhami Hikmat**, Al Ja'afreh Mohammad, and A. El Saddik Abdulmotaleb, "Ontology based framework for Tactile Internet Applications" in Smart Multimedia, 2018 (pp. 81-86). *Springer, Cham.*

REFEREED CONFERENCE PAPERS:

e) **H. Adhami**, M. Aljaafreh, and A. El Saddik, “Ontology based framework for Tactile Internet Applications” in 2019 International Conference on SMART MULTIMEDIA, San-Diego USA.

f) **H. Adhami**, M. Aljaafreh, and A. El Saddik, “Can We Deploy Tactile Inter- net Applications over Wi-Fi, 3G and WiMAX: a Comparative Study based on Riverbed Modeler” in 2019 IEEE International Symposium on Haptic, Audio and Visual Environments and Games (HAVE) (HAVE 2019), (Kuala Lampur, Malaysia), Oct. 2019.

g) M. Aljaafreh, **H. Adhami**, and A. El Saddik, “Experimental QoS Optimization for Haptic Communication Over the Tactile Internet,” in 2018 IEEE International Symposium on Haptic, Audio and Visual Environments and Games (HAVE) (HAVE 2018), (Dalian, P.R. China), Sept. 2018.

h) **H. Adhami**, L. Lina Nachabe, N. Jazzar, and A. El Saddik, “Indoor Localization Smartphone-based Application for Indoor Localization using Measured Wi-Fi Signals”, in The Fourth International Conference on Computer Science, Computer Engineering, and Education Technologies (CSCEET2017), Project: Ontology for WSN, (Beirut, Lebanon), Apr. 2017.

i) **H. Adhami**, and A. El Saddik, “SODHO: Service Oriented Development of Haptics Ontology”, in 2014 IEEE International Symposium on Haptic, Audio and Visual Environments and Games (HAVE) (HAVE 2014),

1.5 - Thesis Organization

The rest of the dissertation is organized as follows:

a) Chapter 2 presents the background information regarding the closely related state-of-the-art works that fit in the domain.

b) Chapter 3 introduces ontology for haptics to present an ontology of the TI applications QoS KPIs to be deployed over 5G and, culminated by our proposed ontology-based framework of the most suitable networking infrastructure deployment for the DT/TI applications.

c) Chapter 4 depicts the traditional and the next generations QoS approaches for DT/TI applications, by validating our ontology outcomes, through three case studies.

d) Chapter 5 presents the concluding remarks about the dissertation and a discussion about the possible future works on the proposed topic.

Chapter 2 - Background and Related Works

The network which could support haptic communications, must ensure all the requirements for a certain Tactile Internet application. Different applications are offered by Tactile Internet, like teleoperation (depicted in Figure 2.1), online gaming, remote surgery operations, and mixed augmented reality. Because of the sensitivity and accuracy of these applications, the round-trip time must be reduced as much as possible.

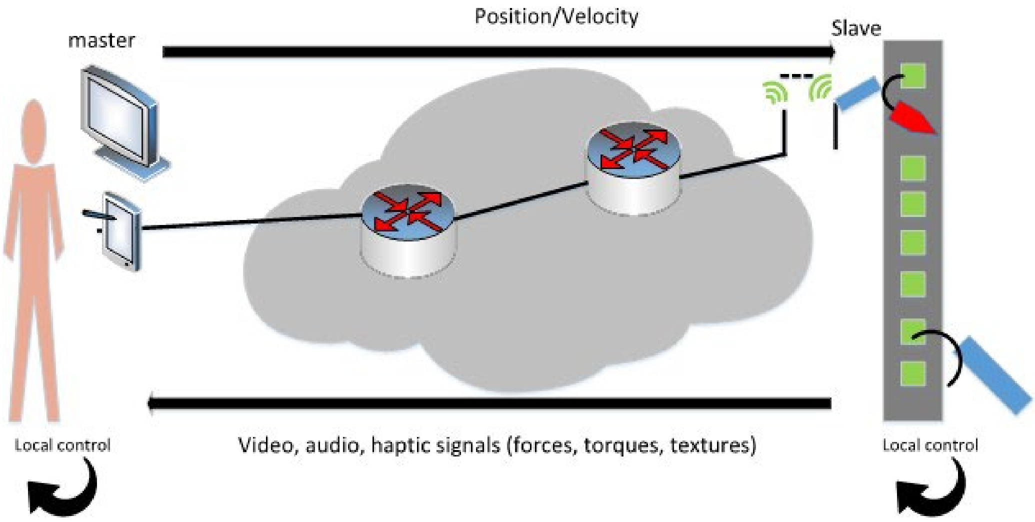


Figure 2.1: An Example of the Tactile Internet Application

Due to the bi-directional communication of velocity, force signals, position and varying environmental conditions, assessing the human perception of delay in haptic teleoperation systems is an issue especially when it is compared to audio-visual delay perception [11]. The ideal situation for a haptic teleoperation/telepresence is zero-delay, zero-jitter, and zero- packet-loss, which is empirically unavailable. Therefore, the realization of the Tactile Internet implores a solid understanding of haptic modalities e.g., kinesthetic and tactile perceptual mechanisms and stimulation principles. For instance, compared to audiovisual session establishment, haptic sessions require that the round-trip-time (RTT) is bound to 1ms which in turn necessitates that the average packet transmission time should be no more than 500 µs.

Further, in order to maintain an acceptable haptic interaction experience, the refresh rate, also referred to as update rate, has to be maintained around 1KHz, whereas the refresh rate for audio and visual modalities are 20Hz and 30Hz respectively. Furthermore, Haptic is more prone to network impairments, as it has been shown that the delay, jitter and data loss rate [5, 12] may adversely affect the quality of haptic rendering and stability. In addition, the bilateral nature, transparency, and reliability of haptic make it challenging to select the most suitable layer of the ISO-OSI network model to establish a robust communication protocol. Indeed, network limitations and impairments still make the bilateral control of haptic communication a bothersome job. Traditionally, the Internet was created with a delivery strategy known as best-effort delivery for data traffic transfer, in which all packets are treated the same way. In the past, when data traffic was more elastic (i.e., it can extend under bandwidth and delay breakages), this technique was acceptable, therefore no Quality of Service (QoS) is guar- anteed. It is obvious that the best effort service offered by regular IP networks is inappropriate to meet the requirements of haptic transmission. The most common QoS protocols and architectures that are recommended by the IETF include Application Layer QoS, Relative Priority Marking, Service Marking, Multi-Protocol Label Switching (MPLS), Differentiated services (DiffServ), and Integrated Services (IntServ) with Resource Reservation Protocol (RSVP). Again, these approaches have been deployed to support the transmission of traditional modalities e.g., video, audio, and graphics. The provision of a specific QoS implementation for multimodal haptic traffic as well as human-computer interaction has got minimal research attention. Therefore, and as indicated in [13], one of the most alarming challenges in the industrialization of 5G is to provide the QoE/QoS implementation needed to support and improve the performance of haptic communication over the Internet.

In the present chapter, we are going to present the different approaches for the Quality of Service for different multimedia modalities along with the different networking protocols that can carry these modalities, especially for the Digital Twin and Tactile Internet applications, to end up with the notion of Ontology that helps us to build our proposed framework in this thesis.

2.1 - QOS Model

As we said earlier, computer networks were traditionally built to carry data traffic using a system known as best effort delivery before the fast growth of the large amount of multimedia content on the Internet. For corporate mission-critical applications and real-time services, this best-effort solution is incapable to ensure certain and dependable end-to-end packet delivery. The recent appearance of new multimedia application classes has underlined the necessity for the creation of new standards that can handle their properties. This has lately been implemented in the shape of a Quality of Service delivery method (QoS).

From a network perspective, QoS is defined as a set of service standards that must be met in order to improve the network's overall utility [141, 142]. This can be accomplished by giving higher-value or more performance-sensitive flows priority.

QoS measurements are divided into three categories: network variables, system factors, and application factors. Each group's metrics are influenced in both directions by the metrics of the other two groups.

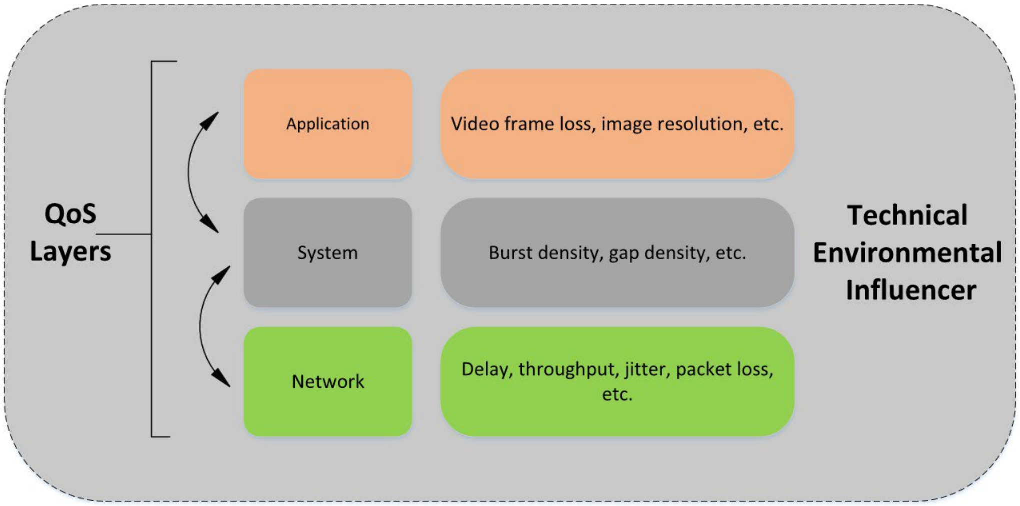


Figure 2.2: QoS Layers (*adapted from* [*148*,183])

The following are the most important QoS indicators, according to various research studies [143, 144, 145, 146, 147, and 31]: delay, throughput, jitter, packet size, arrival model, rendering (update) rate, and data loss rate.

Teleoperation, without a doubt, is a rapidly expanding discipline that combines robotics, telecommunications, and data processing (Figure 2.3). The remote robot's position is controlled by the operator (teleoperator). During contact, interaction forces are measured and communicated back to the operator. Additionally, the operator receives visual and audio input.

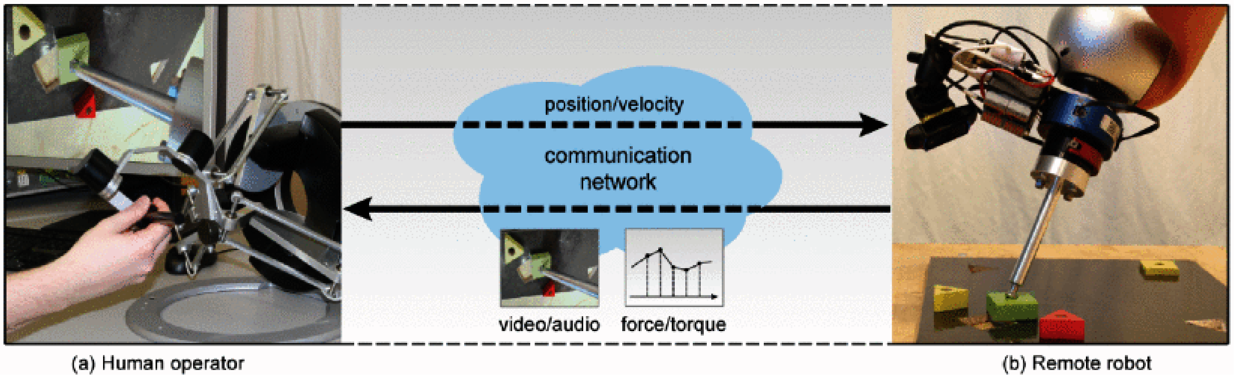


Figure 2.3: Bilateral teleoperation [4,183]

As we are focusing, in our research work, at the networking part, we only concentrate at the metrics of the network level of the above QoS model. Later in chapter 3, the criteria for QoS elements of our interest, are examined. Table 2.1 summarizes the criteria for some of these QoS elements in respect to the aforementioned media types for DT Teleoperation over TI.

QoS Metric	Human-to-Machine Haptic	Video	Audio	3D	Machine- to- Human Haptic Feedbacks	
Packet Type	(Position, Velocity, Force, Torque)	H 265/MPEG 4	Dolby Surround	Mesh, Texture	Kinesthetic Signals	Tactile Signals
Packet Size (B)	1 DoF :2-8 3DoFs :6-24 6 DoFs : 12-48	1.5K	>50	1.5	1 DoF :2-8 3DoFs :6-24 6 DoFs : 12-48	1 DoF :2-8 10 DoFs : 20-80 100 DoFs : 200-800
Jitter (ms)	1.2	30	30	30	2	1
Delay (ms)	1.5	≤ 400	≤ 150	100-300	10	1
Throughput (kb/s)	≥ 512	≥ 2500	≥ 128	≥ 1200	≥ 512	≥ 1000
Data Loss Rate (%)	.01 - 10	1	1	10-Jan	10	0.01
Update Rate (Hz)	≥ 1000	30	20	30	≥ 500	≥ 1000
Arrival Model	Heterogenous (Periodic or Gilbert-Eliot)	Periodic	Periodic	Periodic	Heterogenous (Periodic or Gilbert-Eliot)	Heterogenous (Periodic or Gilbert-Eliot)

Table 2.1 Criteria of QoS Elements [1, 2, 4, 5, and 183]

2.2 - QOS Approaches for Immersed Media Traffic

Several methods have been offered to deploy QoS on standard IP networks. These solutions include service marking, relative priority marking, label switching e.g., (Multiprotocol Label Switching MPLS), static per-hop classification, Integrated Services (IntServ) and Differentiated Services (DiffServ) [14, 15, 16].

IntServ follows the signaled QoS model, which means end hosts signal their QoS requirement to the network. On the other hand, DiffServ works on the provisioned QoS model, where network devices are set up to provide service for multiple aggregated traffic called classes. An overview of the two approaches that is used to implement QoS are presented in the following subsections:

2.2.1 – Integrated Services (IntServ)

The IntServ framework was designed to give individual sessions with personalized QoS guarantees. It offers services on a per-flow basis, with each flow consisting of a packet stream with a shared source address, destination address, and port number. IntServ routers must keep track of each flow's condition. The following are the two most important IntServ features:

Reserved Resources. The router needs to know how much of its resources are now allotted for active sessions.

Call Setup or call admission. A flow that requires QoS guarantees must be able to reserve enough resources at each router along the path to meet QoS requirements.

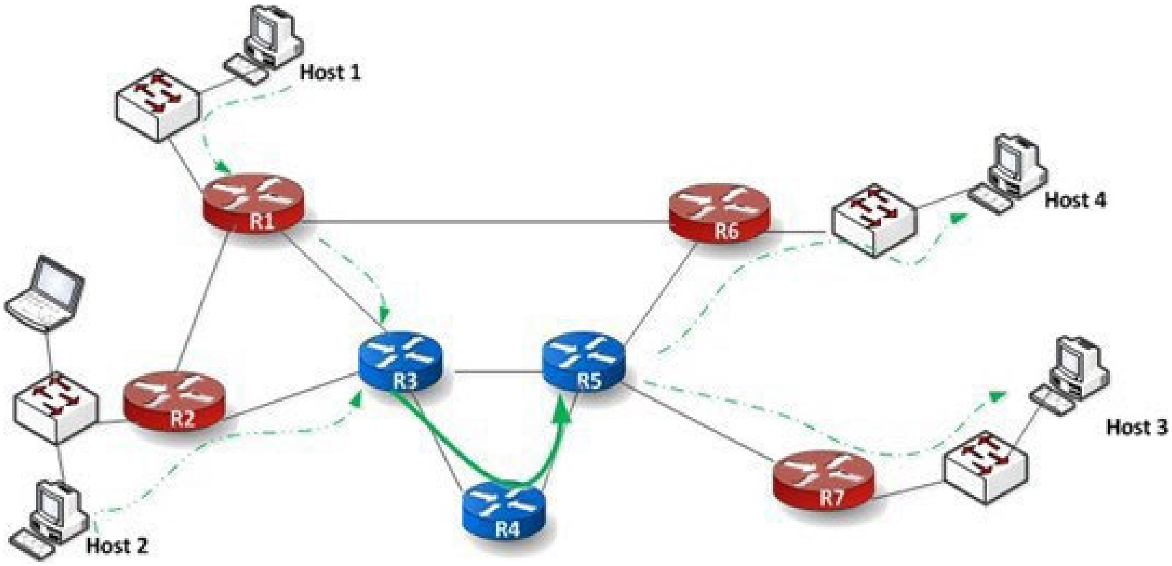


Figure 2.4: A simple DiffServ network Example

IntServ has three classes: best effort, guaranteed service, and controlled load service. Moreover, it depends on the Resource Reservation Protocol (RSVP) in signaling and reserves the appropriate QoS for each flow in the network. A flow in IntServ defined as individual data stream between two applications and is identified by source IP, source port number, destination port number, and transport protocol. Limited scalability is the main draw- back of IntServ since each device along the path of packets such as routers, switches, server, and PCs need to be aware of RSVP and able to send the signaling of the required QoS. To overcome this limitation other protocols are introduced such as Refresh Reduction and Reliable Messaging (RSVP), proxy RSVP and RSVP scalability enhancement.

2.2.2 – Differentiated Services (DiffServ)

In order to support different types of applications and customers' requirements in scalable approach, DiffServ is introduced to provide QoS for aggregated traffic level instead of per-flow state [4, 17]. In DiffServ, packets are aggregated into classes that receive different treatment in the network. Complex operations are pushed out to the edge routers and simpler operations done by core routers. In fact, this approach is scalable, flexible, and better than best effort and it also eliminates RSVP signaling. In addition, it reduces the amount of maintenance required compared to Integrated services (IntServ). Next section is exploring DiffServ in more details and illustrating the mechanism and architecture of

DiffServ by using basic scenario.

Illustrative Scenario

In order to illustrate the architectural components of differentiated services, let us start from simple network shown in Figure 2.4. In fact, we aim to introduce the basic concepts and the key aspects of DiffServ.

Figure 2.4 shows a simple network consists of two router categories, edge routers (red) and core routers (blue). Each category has a specific task that handles any incoming packet. If we assume that Host 1 sending to Host 3, then all packets will initially reach router1 which is edge router. The main job of edge routers is packet classification and traffic conditioning. All packets coming from Host 1 will be marked by setting the differentiated services (DS) field of the packet's header with the proper value. Indeed, the mark of each packet identifies the class of traffic to which it belongs. As a result, each class of traffic will receive different treatment within the core network. Now packets coming from Host 1 already marked at the edge router pass to core routers. These routers will inspect the DS marking of each packet to find specific information in order to know how to handle the packet. According to that information each packet will receive the proper forwarding treatment. This forwarding treatment is called Per- Hop Behavior (PHB). PHB is associated with packet class. Moreover, PHB will influence how router buffers and link bandwidth are shared among the competing classes5 of traffic. An important note about DiffServ architecture is that router's per-hope behavior will be based on packet marking, so routers will aggregate packets with similar marking.

DIFFSERV Architectural Model Classification and Conditioning

All packets exchanged between DS domains must pass through boundary node of each domain. If a packet leaves a DS domain will pass through egress node and all arrival packets will pass through ingress node. In fact, a DS boundary node acts as ingress and egress depending on traffic direction. Classifying, marking and conditioning packets are done in the boundary nodes (edge routers) by traffic conditioner. A traffic conditioner consists of four components: Classifier, Meter, Marker and Shaper/Dropper.

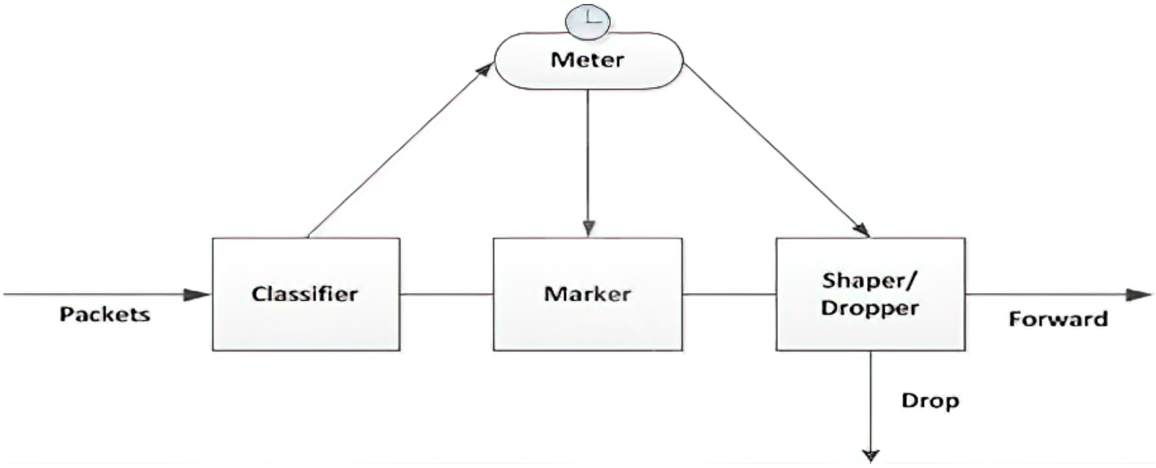


Figure 2.5: Logical view of packet classification and traffic conditioner

Moreover, traffic conditioner makes sure that the packet that passed to the core nodes inside the domain are correctly marked with proper PHB since each DS domain can have different group of PHB that treated differently in each domain. Figure 2.5 shows the logical view of classification and marking and conditioning functions of edge node. Packets arrive the ingress node will first be classified. A classifier selects packets based on fields in the packet header, for instance, source and destination addresses, source and destination ports and protocol ID. Then it forwards the packets that match classifier rules for marking and additional processing. In DS model there are two types of packet classifiers:

Multi-Fields (MF) classifier, this type looks at numerous fields in a packet, including the source and destination addresses, as well as the source and destination port numbers. MF classifiers allow you to set a packet's forwarding class and loss priority depending on firewall filter rules.

Behavior Aggregation (BA) classifier and this type will classify on the bits in the DS field only.

In some cases, end users may have agreed on specific traffic profile in the Service Level Agreement (SLA). This profile contains peak rate as well as packet flow. Traffic meter will measure if incoming packets that selected by classifier conform the agreement and traffic profile and then passes state information to other conditioning functions in order to trigger the proper action for each packet. The actual action is whether to immediate remark, forward, delay, or drop a packet in a policy issue determined and implemented by network administrator.

Marker will set the DS field of incoming IP packets. The PHB is set in the first 6 bits of DS field and then forward the marked packet to core routers. In core router, the marked packet will receive proper treatment based on the SLA between client and service provider. As mentioned above, each DS domain can have different group of PHBs, so the packet is marked when it enters to DS domain and is remarked when it leaves the DS Domain as well.

If the incoming packets do not conform the traffic profile, the shaper will delay these packets in order to make the stream conform to it. A shaper's buffer is usually finite in size, and packets could be discarded if there is no more space to keep the delayed packets. Policing stream is the process of discarding some or all packets in a traffic stream in order to bring the stream into compliance with traffic profile. Dropper is responsible for this process and it is implemented as a special case of shaper by setting the buffer size to zero.

The SLA also contains the details of the Traffic Conditioning Agreement (TCA) that specifies classifier rules. Traffic conditioner will fulfill the SLA by following the details in the TCA which contains all details about metering, marking, discarding, and shaping of packets. The TCA information must be available in all boundary nodes of any differentiated domain to assure that packets passing between different DS domains receive the same service in each domain [14].

Per - Hoper Behavior

Per-Hop Behavior (PHB) is a key component of DiffServ architecture. RFC 2475 defines PHB as “a description of the externally observable forwarding behavior of DiffServ node applied to a particular DiffServ behavior aggregate”. If we analyze this definition we will notice the following important points: Different classes of PHB will receive different treatments or performance (behavior)

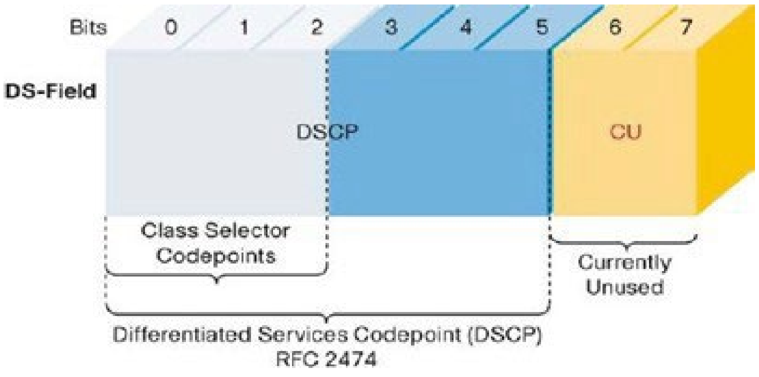


Figure 2.6: DS field

The definition does not force specific implementation to achieve the behavior or performance. So PHB does not require specific packet queuing to be used to get particular behavior.

Each performance must be measurable and observable.

Figure 2.6 shows the differentiated Services (DS) field, it has two unused bits. The six bits called Differentiated Services Code Point (DSCP). Using DSCP we may have up to 64 different aggregates classes. In fact, DiffServ classification and marking revolve around DSCP [17].

In the followings a brief explanation of PHB standards is presented:

Default PHB: It specifies that packets marked with DSCP zero in this case, these packets will receive the default treatment in core routers which is best effort. Moreover, if the DSCP is not mapped to any PHB in the domain then it will be considered as a default PHB.

Class – Selector PHB

This standard is introduced for backward compatibility with IP-precedence scheme. DSCP values are of the form “xxx000”, where x is 0 or 1, in this case the PHB associated with class-

-selector code point will retain to the same forwarding behavior as the node that implemented IP-precedence based classification and forwarding.

Assured Forwarding (AF) PHB divides traffic into four independent AF classes. Within each AF class, packets are further partitioned and assigned one of three different levels of drop precedence. For instance, an IP packet that belongs to an AF class i and has drop precedence j is marked with the AF code point AF_{ij}, where $1 \le i \le 4$ and $1 \le j \le 3$.

Expedited forwarding (EF) provides a low-loss, low-latency, low-jitter and assured bandwidth service. At any point of time the class of traffic can be guaranteed to get enough bandwidth and will not get less than the minimum configured rate. Moreover, if the other classes of traffic are overwhelming the router, enough of router resources must be available to handle the traffic of EF classes to get the minimum bandwidth. In fact, EF is suitable for applications such as VoIP that requires very low packet loss, low delay, low jitter, and guaranteed bandwidth. It is also suitable for video streaming and any application that needs robust network treatment [14].

DS Domain

A DS domain normally consists of one or more networks under the same administration. Figure 2.7 shows three domains each one has different QoS requirements and according to its network administrator must be aware of how to use the proper measurement techniques to fulfill SLA between domains. As mentioned above DS boundary nodes (ingress and egress) are responsible for classification and marking. Based on the SLA packets might be marked when it entered the domain and remarked again when leave it.

Queue Scheduling

It is described as set of algorithms and mechanisms that are used to manage the way packets are sent from an input to output in a router. Queue scheduling has an essential role in optimizing IP operations and improving QoS parameters. The main objectives of using Queue Scheduling in QoS are as the following:

1. Sharing bandwidth fairly
2. Guaranteeing QoS parameters like bandwidth and delay for certain types of applications
3. Reducing jitter
4. Preventing bandwidth starvation among IP users.

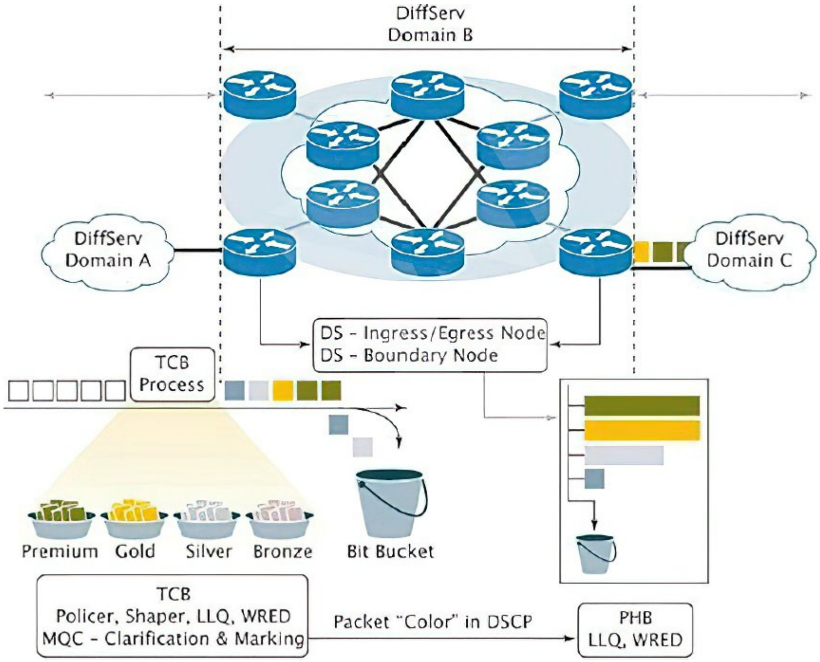


Figure 2.7: DS Domains and DS Architectural Overview

Some of the most frequently used algorithms in IP networks are:

- First-in first-out (FIFO): It also called first-come first-served algorithm (FCFS). It is the simplest algorithm that transmits packets from input to output queue based on their arrival time regardless of their size, type, contents, or any other packet characteristics. One of the advantages of FIFO is its simplicity, it takes less processing than other techniques and therefore it can be a good choice for IP routers with very high-speed interfaces. However, with heavy traffic or during congestion, FIFO creates a problem for QoS enforcement. This technique can't be a good choice for real time applications such as haptic for tele-medicine for many reasons, first, FIFO executes tail drop arbitrarily and this is undesirable for most critical applications because of the lack of criteria in their dropping, and might happen that a packet with low priority passes through while real time packet is dropped out. Moreover, since this algorithm doesn't distinguish between packets that have different lengths, real time packet will suffer long delay while long packets are transmitted ahead of it.

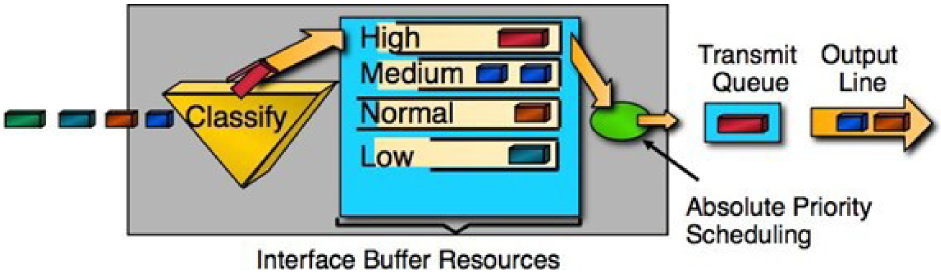


Figure 2.8: Priority queuing

- Priority queuing (PQ): It is a very common technique used in IP routers. In PQ algorithm, Figure 2.8, n queues are used to transmit packets and those queues are assigned relative priorities (0 to n-1). These priorities are listed in a high-to-low order, with higher-priority packets being served first and packets in queue k being served only if queues 0 to k-1 are empty. Traffic may be prioritized by the type of packet (IP, IPX or other), or by application type (haptic, VR, VOIP or other). The advantages of this technique are high throughput, lower delay, and higher bandwidth to packets with higher priority queues. One drawback of this technique is the queues with low priority may suffer resource starvation because of its order. In general, PQ technique is considered to be as the most primitive algorithm to queue packets. In order for packets to be classified on a priority queuing interface, policies must be created on that interface.

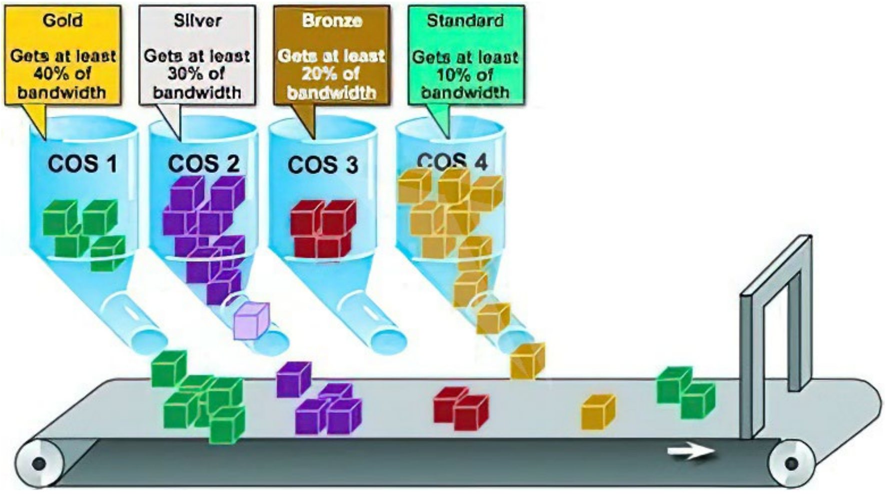


Figure 2.9: Weighted-Fair Queuing (WFQ)

These policies filters traffic into one of four priority queues (High, Medium, Normal and Low). In case any traffic that is not filtered into a queue is placed in the normal queue.

- Round-Robin (RR) and weighted round-robin queuing (WRR): In RR algorithm, packets are classified and transmitted to m queues. As in PQ algorithm, classification is done based on type of packet or type of application. The queues in this technique are serviced in order of 0 to m-1 and one packet at a time. RR algorithm solved the problem of starvation because all queues are serviced periodically by RR discipline. However, because RR does not take packet size into account, certain small critical packets may have to wait for extended periods of time in queues while large noncritical packets are processed. Also, RR can't provide guarantees for bandwidth or delays. Another type of RR is Weighted Round-Robin (WRR) that can serve more than one packet for a particular queue.

- Weighted-fair-queuing (WFQ): It is an algorithm that is used to ensure fairness, to offer predictable packet flow behavior, and to avoid resource starvation. The Generalized Processor Sharing (GPS) method is approximated by WFQ. WFQ's general fairness features are as follows:

1) Small packet traffic is not jeopardized and is given effective priority.
2) Large packet traffic does not consume a lot of bandwidth.
3) As demonstrated in figure 2.9, using weights for queues allows for an intrinsic allocation of greater resources (bandwidth) for time-sensitive traffic.

The authors in [18] proposed a configuration guideline for IP DiffServ that includes multiple type of classes. The work induced a new real-time service class intended for interactive and variable rate inelastic applications that require low jitter and loss and very low delay. The authors recommended that this class of application has to be con-figured with a class selector CS4 while setting the Differentiated Services Code Point (DSCP) marking scheme with a PHB by Assured Forwarding AF21-23. The study in [19] investigated the effect of QoS required to transmit haptic stream on top of UDP in a Distributed Haptic Virtual Environment (DHVEs). The outcome of the study depicted that applying Weighted Fair Queuing and Class-based weighted fair queuing improved the transmission of a haptic stream in IP QoS-enabled architecture. The study was extended in [20] to study different levels of service forwarding applied to haptics and voice traffic. Comparing both experimental and simulation results, the author concluded that in order to have an acceptable haptic and audio experience, the haptic and audio CBWFQ classes have to be DSCP marked with at least AF22 or expedited forwarding (EF).

Software Defined Networking (SDN)

The supervision and the dynamic management of resources requires the configuration (and re-configuration) of all network nodes and is very demanding. This makes deploying the traditional QoS protocols i.e., Intserv and Diffserv, an arduous task. As a result managing flexible traffic and simultaneously establishing precise and dynamic QoS requirements is still crucial and challenging in the internet. On the other hand, the efficient and fast adjustment of resources to the actual traffic necessity is an important characteristic required to be delivered by Next Generation communication. The latter will also be a vital enabler for the tactile internet.

The software defined networking (SDN) [21] allows flexibility and adaptability in network administration. Software-defined networks (SDN) are characterized by "the decoupling of control and packet-forwarding planes in the network "[22]. By applying programming and supporting application execution and security, SDN enables the network to legally associate with applications, therefore creating a selectable network design that can be modified as required. Most Enterprises are using SDN since it enables them to send their applications more swiftly while reducing at the same time expenses related to deployment and operations. IT heads using SDN can oversee and provision their network services from an incorporated point. SDN applies open APIs to help keep up network control, which makes it a network model providing programmatic management, control and network asset optimization. When SDN decouples the network design and traffic engineering, it isolates them from their central network infrastructure, therefore resulting in network control. This splitting allows the use of OpenFlow and other open protocols which can access network switches and routers that regularly utilize exclusive and generally closed firmware by applying globally aware software control at the network's Edge. SDN attempts to create a computer network by dividing the system into the accompanying separate planes; it, therefore, helps clients virtualize their hardware:

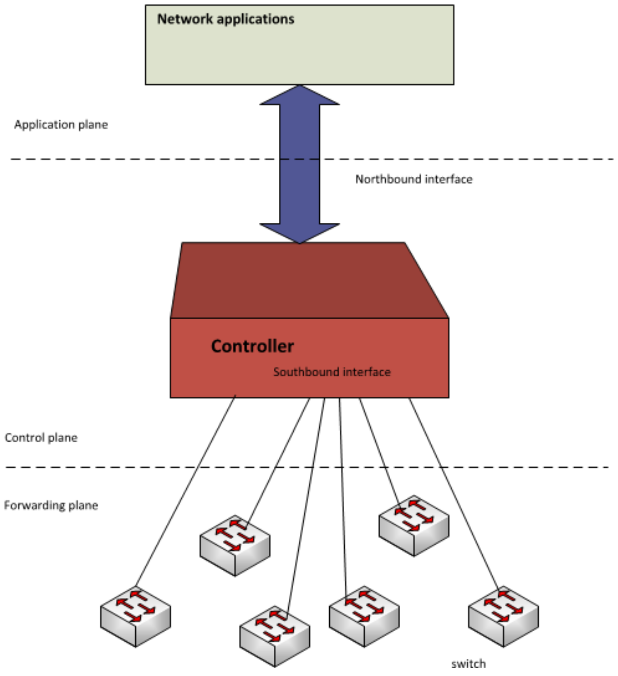


Figure 2.10: SDN Layers

The control plane allows the performance and fault management of NetFlow depending on the type of the deployed protocols, which makes it useful in managing devices designs that are remotely associated with a software defined network.

The data plane advances traffic to its ideal destination. It does so with the help of the control plane which indicates the past streams to follow by utilizing the flow control before traffic reaches the data plane. Thus, administrators can effectively work with the software defined network and manage the network. When it was first implemented by important enterprises such as Google and Amazon, SDN had many benefits:

It helped them make adaptable server farms; it allowed them to encourage network resources and new cloud-based server development and, last but not least, it unburdened the IT directors by reducing their workload. SDN consolidated the efficiency of the up-scaling procedure for these huge organizations and appealed to other important ones which immediately adopted SDN in order to better their up-scaling effectiveness. The framework of SDN is summarized and depicted in figure 2.10. Paragraph 2.3.3 provides an in-depth insight at SDN architecture.

APPLICATION BASED QOS SCHEMES

In terms of QoS at the data link layer, Multiprotocol Label Switching (MPLS) is defined as a routing technique in telecommunications networks; it uses short path labels instead of long network addresses to channel data from one node to the next; this will help avoid complex lookups in a routing table and will accelerate traffic flows [23].

Consequently, thanks to MPLS, we notice an improvement in end-end QoS metrics for multimedia Communications such as low latency and jitter. In terms of QoS schemes at the application layer, and regarding haptic, visual, auditory, and scent data dissemination, the author in [24] suggested an Adaptive Multiplexing Framework (ADMUX).

The network resources are fairly administered by a statistical multiplexing scheme used by ADMUX to insure QoS.

Adaptive Multimedia (multiple multimedia modalities) Delivery Solution (ADAMS) [25] is another client-server framework equipped by multiple modules: its role is to refine the multimedia data streams after considering information submitted by the client. Cizmeci et al. [11] propose a visual haptic multiplexing scheme for teleoperation over constant bitrate (CBR) communication links. According to this technique, the shared channel is divided into 1-ms resource buckets and the size of the transmitted video packets is controlled as a function of irregular optic transmission events that are generated by a kinesthetic codec.

2.3 – Networking Protocols to carry out the communication of Digital Twin System

The Digital twin architecture is based on the interaction of multimodal exchanged data between the real and virtual world. In other words, the Digital Twin system works like a closed-loop system with feedback. Adding human experience as part of this loop can better correct and improve the entire Digital Twin experience system. This is exactly the embodiment of the interactive performance of the DT system. It should be noted that several studies have looked at the benefits of local multimodal media systems and how users perceive this content. [26, 27, 28, and 29]. On the other hand, there is currently a research gap in the area of multimodal information communication over the Internet. A good communication protocol for such data must adapt to and/or match the needs of the user, application, modality, and network. When building the schema of the future tactile Internet 5G infrastructure, certain needs must be taken into account. In fact, interactivity, collaboration, co-presence, and togetherness are impossible to achieve without addressing the issue of communication. As a result, a thorough examination of existing communication frameworks capable of disseminating information created by multimodal systems without compromising the rendering quality of the incoming content is critical. In this chapter, we go over the most comprehensive list of technical problems that must be overcome in order to implement a proper multimodal communications protocol.

2.3.1- Communication Protocols for Multimodal Systems

To the author's knowledge, there are few protocols/frameworks that consider the streaming of five senses media formats while meeting the aforementioned communication problems. Figure 2.11 shows sixteen possible transport and application layer protocols based on [10, 30, and 31]. We present a quick summary of the most important protocols in the following paragraphs.

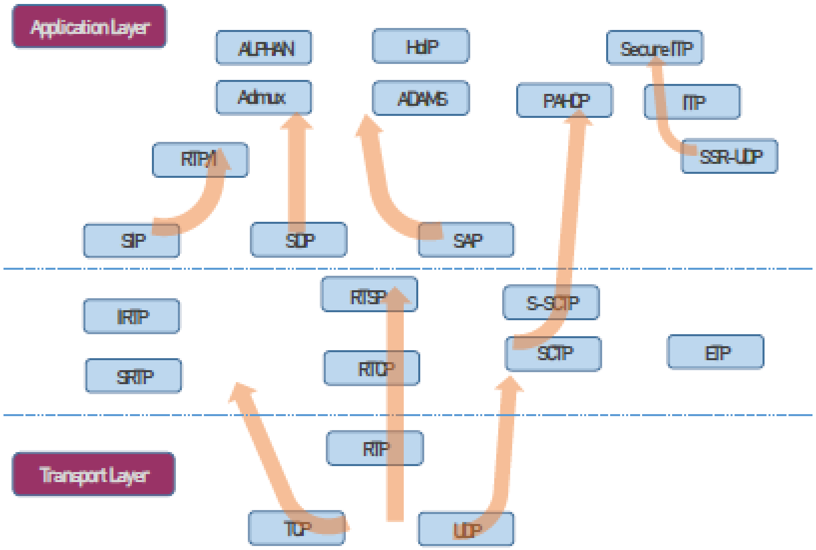


Figure 2.11: Communication Protocols Summary

Several Internet-based distributed applications use the general transport-layer protocols Transmission Control Protocol (TCP) and User Datagram Protocol (UDP). TCP uses error, sequence number, loss, and duplication restrictions to provide dependable and connection- oriented services. Any multimedia application's QoE (and QoS) can be harmed by these strategies. TCP also works by establishing a virtual link between two endpoints. As a result, it does not support multicast distribution [32, 33], making it incompatible with collaborative applications. TCP has a large network overhead due to its 20-byte header size, which is especially noticeable when dealing with a modality that demands a rapid update rate, such as haptic applications. TCP behavior, in general, does not suit any multimedia application because it was designed to ensure packet delivery regardless of transmission delay. UDP is another often used generic transport protocol. It's utilized by a type of application that emphasizes best-effort delivery over data transmission reliability. UDP has the minimum network overhead of all the protocols due to its modest header size of 8 bytes and lack of retransmission mechanism. Despite this, UDP is not regarded suitable for the multimodal applications outlined below. First, UDP lacks a buffering system, which causes delays to vary. Second, it fails to offer an acceptable timing mechanism for transferring datagrams, resulting in the failure to meet the synchronization challenge. Third, UDP lacks the multicast functionality that is required to meet the collaboration criterion.

To solve the constraints of TCP and UDP, a new protocol called Streaming Control Transmission

Protocol [34] has been designed. It actually combines the best aspects of TCP and UDP. SCTP is similar to TCP in that it allows for connection-oriented communication, but it goes further by establishing numerous transport streams between end points within an SCTP port. The Stream Sequence Number (SSN) in the SCTP header is used in this process, which is known as SCTP association. Each chunk in SCTP has a common header of 12 bytes. SCTP's selective ACK (S- ACK) mechanism enables dependable services in addition to unreliable communication. It can also enable multi-homing, which means that each end-SCTP user's association can use a pair of IP addresses. This is quite useful for load balancing across multiple pathways. SCTP was originally designed for telephone signaling, but it has now evolved into the Partial Reliable-Stream Control Transmission Protocol (PR-SCTP) [35]. The PR-SCTP and SCTP headers are the same size. In actuality, it's an SCTP data mode extension that's unreliable. The data retransmission rate is adjusted in this protocol based on the content's level of reliability inside a given association. It contains numerous rules that allow varying data dependability weights to be defined, resulting in lost data being resent until a given reliability threshold (message lifetime) is met. When the sender reaches the reliability level, the unacknowledged data retransmission is terminated, and the receiver is notified with Forward TSNs to ignore any pending packets and shift the cumulative ACK point to the news packets. As a result, based on the modality type, its needs, and network conditions, the end- user can dynamically assign the stream's reliability level. In [36], the authors compared the performance of PR-SCTP, TCP, and UDP for MPEG-4 multimedia traffic in a mobile network. PR-SCTP shows promise in terms of maintaining a low delay and bandwidth in that investigation. Unfortunately, PR-SCTP has not been tested for new multimedia systems with new modalities as haptic or 3D graphics. Light TCP (LTCP) was proposed to solve the problem of the general TCP's inability to distinguish between active and old messages [33, 37]. By incorporating such a method into the communication protocol, the amount of updated traffic will be drastically reduced. Message obsolescence is the term for this strategy. As a result, LTCP has an updatable queue mechanism that allows the updated message with the obsolete flag to be discarded while it is being sent. From the sender's perspective, a key update message is placed at the end of the queue, with a marker beyond it indicating its placement and significance in comparison to other messages. Updates to normal messages that are no longer relevant will be removed and replaced with new normal messages. When no update messages are necessary between the older message location and the queue's end, this replacement occurs. According to congestion control, the messages in the queue will be consolidated and transmitted as a single IP packet. If the received messages are newer than the previously received messages, they will be delivered to the program on the receiver side. As a result, LTCP does not support receiver buffering. In several ways, LTCP is similar to general TCP: update messages are queued on the sender side, acknowledgment is per packet sent, sliding window and congestion management are both employed, and a sequence number is used. In comparison to the two generic TCP and UDP protocols, LTCP has key update message and aggregation functionalities. LTCP, on the other hand, lacks quick processing, which is critical for multimodality interaction communications.

[38] created the Interactive Real-time Protocol (IRTP). IRTP is a transport protocol that can swiftly re-adapt to meet both critical and real-time requests. It does this by imitating the two generic transport protocols TCP and UDP. TCP is used to transmit critical data (data that must be sent to the receiver regardless of the additional time delay), whereas UDP is used to transport real-time streams (data that has to be delivered as fast as possible). It uses a windows size technique to provide flow and congestion control using the Trinomial Theory. The Arrangement Buffer (ARB) and Application Buffer (APB) are used to control errors, respectively. The IRTP header is made up of four segments: COMMAND, SOURCE IDENTITY, SEQUENCE NUMBER or ACKNOWLEDGE NUMBER, and CHECKSUM, for a total header

size of 9 bytes. It suits the streaming of Internet Robot Control applications where short data per frame is transferred often because it is a short-headed protocol. [39] has shown, however, that in some congested settings, IRTP might cause unwanted delays in bilateral teleoperation.

The Quality-Oriented Adaptation Scheme (QOAS) [40] is a proposed application layer protocol for providing an adaptable client-server multimedia streaming solution over IP architecture. The protocol addressed the tradeoff between the number of concurrent end users who can utilize the multimedia system and the transmission-related parameters required to transmit perceived media content, such as throughput, packet loss, latency, jitter, and so on. The QOAS server has four high-quality versions of the same multimedia content for this purpose. A subjective technique known as the Quality of Delivery Grading Scheme (QoDGS) is utilized on the end user side to evaluate the quality of the delivered material and provide a feedback report to the server. The server then uses a Server Arbitration Scheme (SAS) to filter the incoming feedback depending on the end-user preference, and refines or lowers the quality of the provided information accordingly. The suggested model's fundamental flaw is that QOAS content can only be expressed as an MPEG-2 stream, limiting its applicability to new emerging modalities like haptic and olfaction. Furthermore, the user feedback packet (4- byte content) is contained in a 20-byte IP header, an 8-byte UDP header, and an 8-byte RTCP receiver report packet header, resulting in a 40-byte overhead per feedback packet. For collaborative and interactive media applications, this circumstance could create a bottleneck.

Application Layer Protocol for Haptic (ALPHAN) [41] is an application protocol that prioritizes and optimizes haptic, VR, and audiovisual transmission using a multiple buffer technique. ALPHAN is based on UDP and employs the Haptic Application Meta Language (HAML), which is a rich metalanguage that enables for customization of application needs. The MPEG standard inspired ALPHAN since it divides data flow into three basic frame types: I, P, and B. It uses a retransmission approach similar to TCP, in which key updates are kept until acknowledged. More precisely, it employs a dependable sending strategy for particular updates (I packets), whereas standard updates (P, B) are unaffected. By including the time stamp and sequence number fields in its packet header, it maintains inter and intra-stream synchronization. It also employs the Multiple Buffering (MB) approach, in which each application object allocates a sending-side buffer. This allocation ensures that each object update is sent in a unique way, whether for user-based prioritizing or preference-based applications. Because ALPHAN is a layer 5 protocol, each overpassed UDP packet incurs an additional 16 byte overhead. This is a disadvantage, especially when no adaptive compression strategy is utilized to reduce the ALPHAN application's packet rate. Finally, because it does not address multicasting, it is not a collaborative protocol. For haptic, visual, auditory, and scent data dissemination, an application protocol called Adaptive Multiplexing Framework for Multimedia Communications (Admux) [24] is used. It is based on application needs and network conditions that determine the QoS requirements for haptic, audio, and video. Admux seeks to merge many multimedia channels into a single transport stream. Admux, like ALPHAN, uses the HAML to allow multimodal applications to smooth Admux communication protocols based on their concurrent needs. The MB scheme is also used. Admux beats ALPHAN by adopting Statistical Multiplexing, which evenly distributes network resources rather than parallel communication. The protocol was tested on the HugMe system, an interpersonal telepresence system, and the findings revealed that it was adaptable to communication situations and application events. Admux's header does not provide a multicast field by default, implying that it is not appropriate for multi-user interactions. Due to multi-level fragmentations and packetizations, the framework also causes additional delays. The HugMe system simulation was tested using haptic audio video streaming. Furthermore, assuming that the multimodal application includes a HAML description file, this can be a major flaw that limits its usability on HAML programs and platforms that aren't enabled. Last but not least, its implementation lacks an error resilience mechanism, which is a vital component of any multimodal system's stability and transparency.

Supermedia Transport for Teleoperations over Overlay Networks (STRON) [42] is a protocol that is designed to provide forward error correction as a transport method that aids in the delivery of a quick and reliable service. It was designed to distribute packets across multiple decoupling channels of overlay networks. STRON also outperforms TCP in terms of offering a stable and rapid contact. It provides a transport service that does not require ACK or retransmission due to the use of Reed Solomon codes. TCP Friendly Rate Control (TFRC)

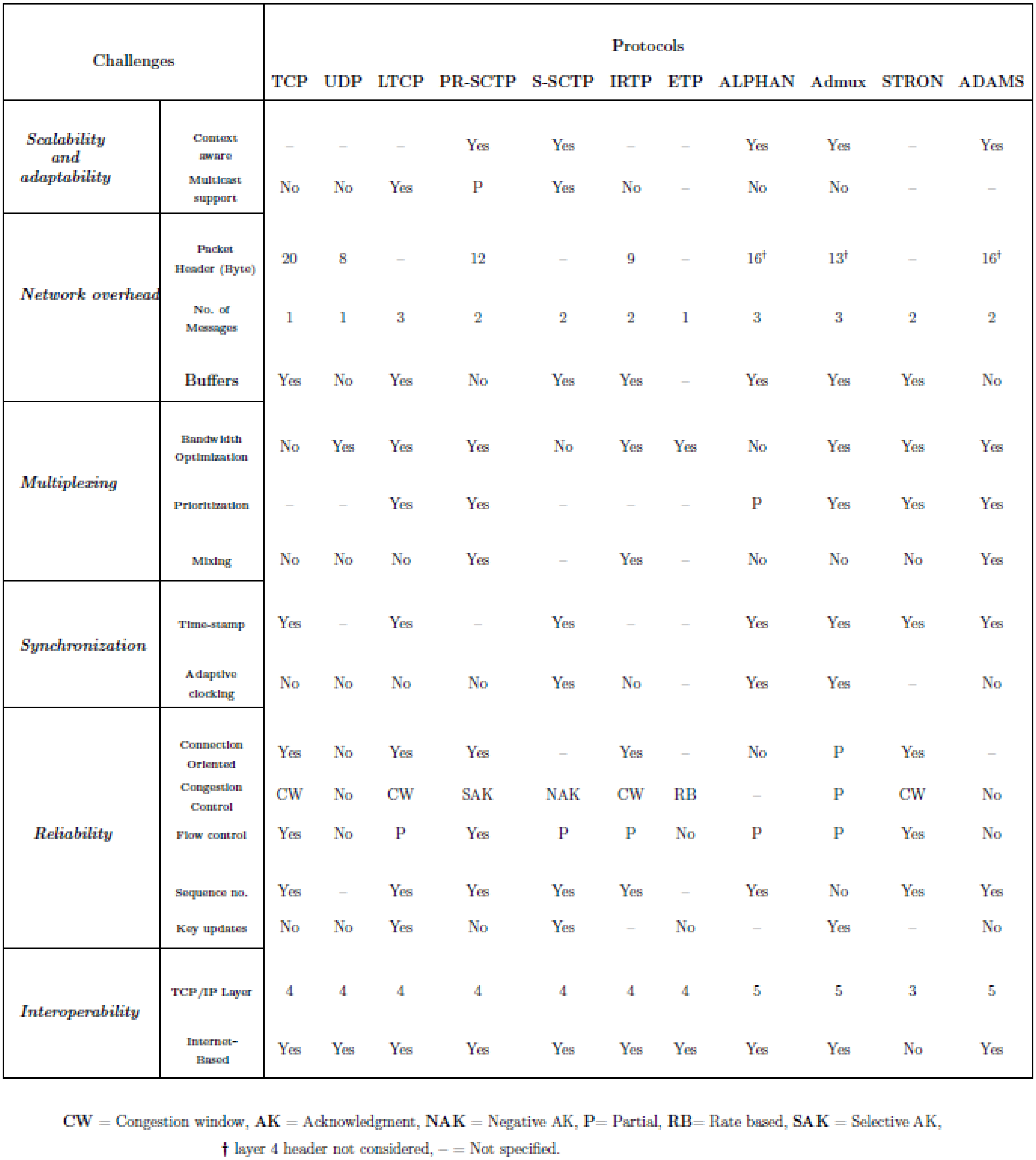
[43] is a congestion control protocol used in STRON for each overlay path. In [44], the authors created a QoS management framework for super media teleoperation systems that are delay- sensitive. Delay-sensitive streams are encoded and delivered across several overlay links using appropriate codecs. The framework employs a haptic data transfer mechanism that employs adaptive packetization and a priority filtering method to reduce transmission rates.

According to the consequences of haptic data loss and delay, it tries to modify haptic transmission, loss rate, and buffering time to network status variations. To offset jitter to a minimum delay, a synchronization mechanism known as dead reckoning is performed. When compared to existing transport schemes, the framework offers unique characteristics such as priority-based filtering and network-adaptive haptic event aggregation, which have been shown in experiments to improve transmission rates. There is a protocol called Efficient Transport Protocol for exclusive interactive applications like haptic (ETP) [45]. It aims to reduce round trip time (RTT) by reflecting network congestion circumstances in the Inter-Packet GAP (IGP), which is the time elapsed between two consecutive delivered packets. As a result, the unstable bandwidth times are detected, and the available bandwidth during transmission is increased correspondingly. ETP uses six transmission conditions for efficient bandwidth: Fast- Decreasing, Look, Increase IPG, Slow Decrease IPG, Stability IPG, and Stability Max. The use of the IPG feature allows ETP to provide congestion control. Using the UDP protocol, it distinguishes between data transit and feedback channels. ETP is well suited to interactive applications in which data is frequently exchanged, such as haptics. Despite the fact that ETP was designed for this purpose, it lacks critical functionality like as multicast, flow control, and key updates, which are among its major flaws. The authors provide a paradigm for video and sensory data distribution termed Adaptive Multimedia Delivery Solution (ADAMS) in [25]. Their concept aims to stream a three-dimensional model that incorporates a video source, sensorial data, and network bandwidth optimization. Their architecture involves employing MPEG-7 as the description technique to combine three sensory sources (air motion, haptic, and olfaction). Despite the fact that they incorporated various sensorial sources in their framework, their framework is user dependent, which implies that subjects must advise the system administrator of their preferred sensorial effects; in other words, it does not handle all conceivable multimodality combinations. The biggest flaw in this technique is that it adds an extra 16 bytes of overhead for each UDP and TCP packet that is overpassed. When transmitting modalities that require a high refresh rate, this can be a bottleneck problem over non- dedicated networks such as the Internet.

The Hybrid Multicast Transport Protocol (HMTP) [46] was offered as a way to create better virtual collaborative environments. It combines the best attributes that were contributed in Scalable Reliable Multicast (SRM) [47], Reliable Multicast Transport Protocol (RMTP) [48], Selective Reliable Transmission Protocol (SRTP) [166] and Synchronous Collaboration Transport Protocol (SCTP) [49]. Its design is based on a client server architecture. In the same way as RMTP works, HMTP uses a multicast tree to convey messages. It also employs RMTP- style scalability and SRM-style reliability. Normal and key updates are the two types of messages that SCTP uses for transmission. The latter is treated as a reference and must be sent consistently, whereas standard update messages, which are provided on a regular basis, are sent with the best effort. HMTP, like SRTP, sends packets in three different forms depending on the message type. In the same way that SCTP uses the Interaction Stream for synchronization, HMTP does as well. When compared to SCTP, HMTP tests showed fewer errors and faster execution times when adjusting network impairments. HMTP, as utilized by SRM, ensures end- to-end reliability by using NACK messages to reduce end-to-end delay, while increasing overall throughput. It groups users who are in the same location using the HMTP client-server framework. However, users from various or heterogeneous places will not be considered in the HMTP collaboration environment, which is a weakness because today's collaborations entail distinct regions of user engagement. In addition, in CVE and C-HAVE, HMTP does not consider wireless contexts.

A point-to-point Haptic over Internet framework (HoIP) [50] was proposed for haptic data communication to enable a low-latency haptic data transmission environment without impacting the haptic quality experienced by users. Through the existing UDP design, it provides a multithreaded structure for both the transmitter and receiver to ensure reduced processing time. The type field in the HoIP structure specifies whether the processed data is for haptics, haptics-audio, haptics-video, or haptics-audio-video. It also implemented transmission scheduler algorithm in its multiplexer to meet the QoS conditions and improve the user experience in the interactive teleconferencing (includes haptic, audio, video). Due to the packet's header size at both the fifth and fourth levels, it introduces extra overheads as a framework at the application level. Furthermore, giving the media integrating function to the system administrator reveals that HoIP lacks an events-driven (context-aware) feature.

In summary, the suitability of a number of networking protocols and frameworks to handle multimodal communication is examined in Table 2.2.



Challenges		Protocols										
		TCP	UDP	LTCP	PR-SCTP	S-SCTP	IRTP	ETP	ALPHAN	Admux	STRON	ADAMS
Scalability and adaptability	Context aware	–	–	–	Yes	Yes	–	–	Yes	Yes	–	Yes
	Multicast support	No	No	Yes	P	Yes	No	–	No	No	–	–
Network overhead	Packet Header (Byte)	20	8	–	12	–	9	–	$16^{\dagger}$	$13^{\dagger}$	–	$16^{\dagger}$
	No. of Messages	1	1	3	2	2	2	1	3	3	2	2
	Buffers	Yes	No	Yes	No	Yes	Yes	–	Yes	Yes	Yes	No
Multiplexing	Bandwidth Optimization	No	Yes	Yes	Yes	No	Yes	Yes	No	Yes	Yes	Yes
	Prioritization	–	–	Yes	Yes	–	–	–	P	Yes	Yes	Yes
	Mixing	No	No	No	Yes	–	Yes	–	No	No	No	Yes
Synchronization	Time-stamp	Yes	–	Yes	–	Yes	–	–	Yes	Yes	Yes	Yes
	Adaptive clocking	No	No	No	No	Yes	No	–	Yes	Yes	–	No
Reliability	Connection Oriented	Yes	No	Yes	Yes	–	Yes	–	No	P	Yes	–
	Congestion Control	CW	No	CW	SAK	NAK	CW	RB	–	P	CW	No
	Flow control	Yes	No	P	Yes	P	P	No	P	P	Yes	No
	Sequence no.	Yes	–	Yes	Yes	Yes	Yes	–	Yes	No	Yes	Yes
	Key updates	No	No	Yes	No	Yes	–	No	–	Yes	–	No
Interoperability	TCP/IP Layer	4	4	4	4	4	4	4	5	5	3	5
	Internet-Based	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes

CW = Congestion window, **AK** = Acknowledgment, **NAK** = Negative AK, **P**= Partial, **RB**= Rate based, **SAK** = Selective AK,
† layer 4 header not considered, – = Not specified.

Table 2.2: Communication Protocols evaluated according to the requirements in 2.2.1 (adapted from [148], 183)

2.3.2 – Wireless Networks Facilitating the communication of Digital Twin Systems

Figure 2.12 displays a high-level perspective of the wireless world as it transitions to 5G. The figure depicts a multi-dimensional picture of the important design problems that 5G technology will confront in order to deliver future services while also achieving cost-effective resource provisioning and ecosystems, which will be constructed with revolutionary technologies like SDN and network virtualization.

2.3.2.1 - The wireless world's evolution

The mobile communication system has progressed from the first generation (1G) to the second generation (2G) to the third generation (3G) to the fourth generation (4G) or Long-Term Evolution-Advanced (LTE-A) of mobile/cellular communications, with each generation bringing with it service improvements and cost savings. For circuit switched speech applications, for example, 1G (Advanced Mobile Phone System (AMPS)) and 2G (GSM and GPRS) were created. Packet switching services such as multimedia, wide-band data, and mobile Internet services were created for 3G (UMTS) and 4G (LTE-Advanced). Other local, metropolitan, and wide-area wireless/cellular technologies, such as microcells, Femtocells, Picocells, tiny cells, and so on, have been introduced in the meantime.

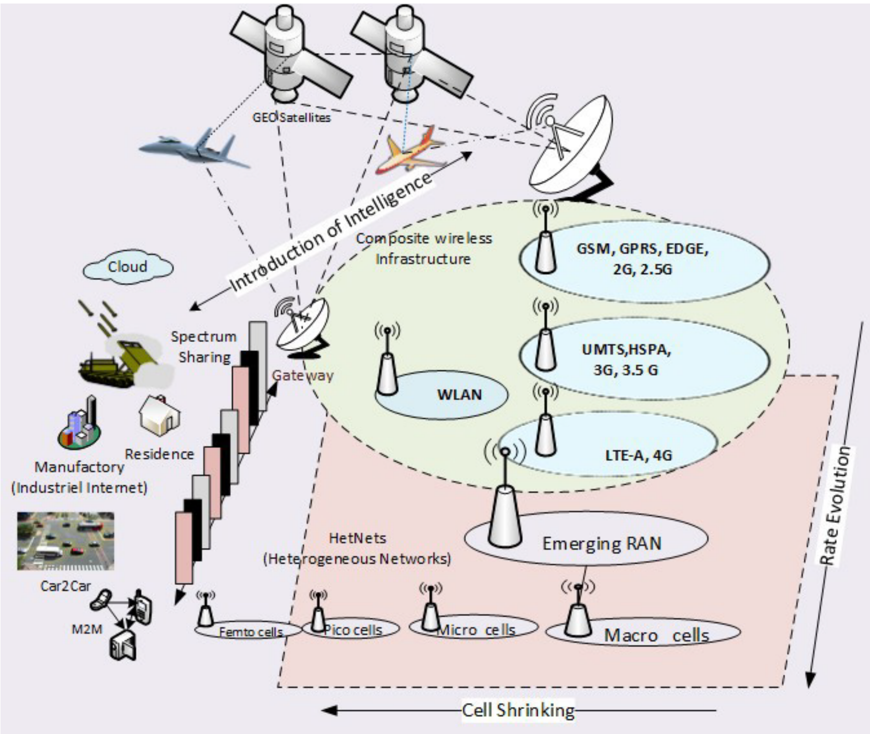


Figure 2.12: A Look into the World of Wireless (adapted from [135])

The other evolution, which arose in the last decade and attempted to leverage heterogeneous wireless communication, included both licensed and unlicensed wireless access infrastructure. It was designed to connect cellular systems to wireless access networks (such as WLAN, WiMAX, and others) in order to improve end-to-end service delivery and application provisioning. As a result, the network was made up of a variety of hybrid infrastructures, resulting in heterogeneous networks (HetNets) [51]. The development of HetNets has created chances to satisfy users and applications in terms of their capabilities to support the new services, driven by both technological and economic incentives. The implementation of application-driven networks is another key path that is predicted to characterize wireless networks beyond 4G and 5G. Application-driven networks are made up of interconnected end-user devices, M2M (Machine to Machine) modules, and a variety of machines, sensors, and actuators, forming the

so-called IoT (Internet of Things), which connects billions of items to the internet to provide big data applications. Parallel to this, in recent years, the development and implementation of cloud-based concepts has emerged as a critical option that can provide businesses with a potentially cost-effective business model. Mobile users, for example, can access cloud-connected devices via the public and private Mobile Personal Grid (MPG). Mobile users can benefit from resource virtualization to satisfy the changing requirements when mobile devices move about within the mobile cloud, given the dynamic needs and supply of network resources with rich resources available in the cloud. In addition, integrating satellites into future 5G networks presents numerous hurdles in terms of supporting flexible, programmable, and secure infrastructure. The cloud, satellites, Big Data, M2M, and 5G will all come together to create an exciting new automated future.

Routing and switching technologies will no longer be used in 5G networks. They will be more open, versatile, and capable of supporting HetNets, as well as evolving more quickly than traditional networks. They'll be able to provide convergent network communication across multiple technologies (e.g., packet and optical networks), as well as an open communication system that can work with satellite systems, cellular networks, clouds and data centers, home gateways, and a variety of other open networks and devices. Furthermore, 5G systems will be self-contained and capable of adapting their behavior to the needs of users in order to handle application-driven networks in dynamic and variable contexts. Future networks will be required to have high levels of security, resiliency, robustness, and data integrity.

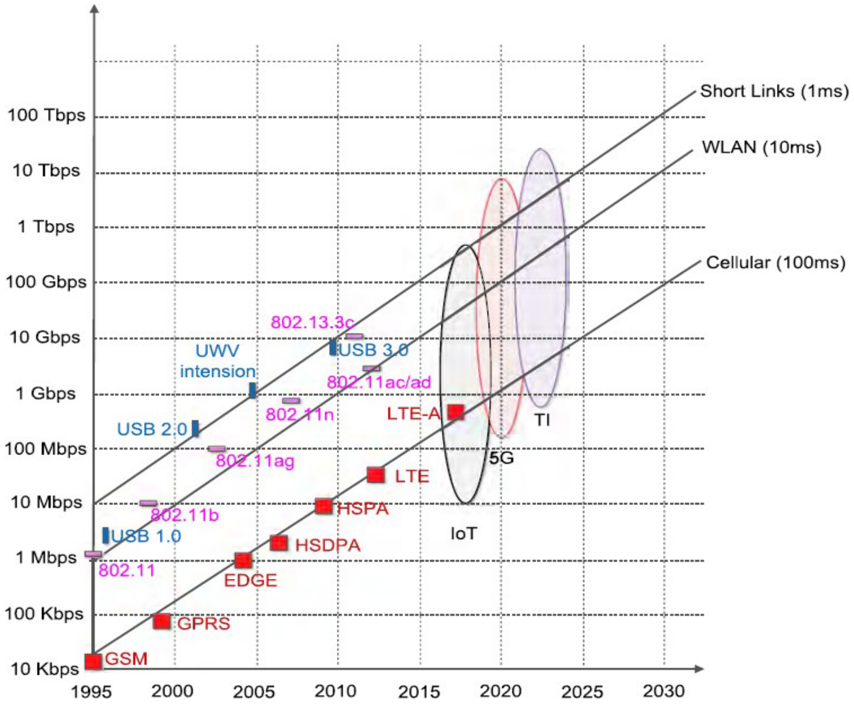


Figure 2.13: Trends in wireless communication across history

2.3.2.2 - Wireless Fidelity (Wi-Fi)

Wi-Fi is a wireless networking technology that employs radio waves to enable high-speed Internet and networking services. Wi-Fi is brief for “wireless fidelity”, and it’s based on the IEEE 802.11 standard. It operates at 2.4 GHz (12 cm) UHF and 5GHz (6 cm) SHF ISM radio frequency bands and can achieve data transfer rates at maximum speed of 1 Gbps (at close range, and running on suitable hardware). Two types of components exist in Wi-Fi, a wireless client station and an Access Point (AP).

2.3.2.3 - Worldwide Interoperability for Microwave Access (WiMAX)

"Worldwide Interoperability for Microwave Access," or WiMAX, is an acronym for "Worldwide Interoperability for Microwave Access." It's an ITU-approved fourth-generation mobile broadband technology that tries to replicate the capabilities of Wi-Fi wireless internet over a mobile phone network using an open protocol (802.16m) [129]. Consider it a patchwork of Wi-Fi hotspots that, rather of being limited to a few hundred feet, may spread over miles and merge, eliminating coverage gaps. It provides compatible devices with fixed and mobile internet connectivity with less interference than regular Wi-Fi. WiMAX subscribers should expect download speeds of 3 to 6 Mbps in the near future.

2.3.2.4 - Third Generation Universal Mobile Telecommunication System (UMTS)

3G UMTS is the third generation of mobile networks. It has the following features: broadband, packet-based text, digitized audio, video, and multimedia transmission at data speeds up to 2 Mbps. Wideband code division multiple access is another name for it (WCDMA). It enables the introduction of many more applications to a global consumer base. New services, such as alternate billing methods or calling plans, are also available. Video conferencing and IPTV are also possible with the increased bandwidth. When UMTS is fully operational, computer and phone users will be able to stay connected to the Internet while traveling and will have the same set of capabilities everywhere they go [128].

2.3.2.5 - Long Term Evolution Advanced (LTE-A)

LTE Advanced is a mobile communication standard and a major enhancement of the Long- Term Evolution (LTE) standard. The first generation of LTE has established a record by achieving maximum downlink speed of 300 Mbps and uplink throughput of 150 Mbps, as well as reduced latency than 3G and some modifications in Rel-9. The advanced version of LTE goals, are:

- Increase data throughput
- Improve flexibility
- Decrease latency
- Increase reliability of data transmission
- Increase in communication efficiency

The LTEA was launched by the 3GPP in Rel-10 and had continued its upgrade through Rel- 11, Rel-12 and Rel-13 to include new features in the communication system such as carrier aggregation (CA), self-organizing network (SON), and many enhancements in the performance of the multiple input multiple output (MIMO) technology. These upgrades had extremely contributed to the improvement of LTE performance which includes a peak data rate up to 1 Gbps in downlink and 500 Mbps in the uplink.

Many more applications that needs huge amount of speed and better QoS to provide smooth services to the users were introduced during that era in the worldwide such as: IoT applications, driverless car, mobile cloud computing, virtual and augmented reality, holographic and 3D call video call, large file sharing and ultra-high definition videos streaming and transmission. [52, 53]

When it comes to LTE network design, the abbreviation SAE (System Architecture Evolution) is frequently used, indicating that the entire network system architecture for LTE has been advanced. The S1 interface connects the base station, named eNodeB, to the core directly. Because there is no network controller like in CDMA, LTE has a considerably simpler architecture. The X2 interface is also used to connect the base stations together.

The functional separation between the Evolved Packet Core (EPC) and the base station (eNB) is depicted in further detail in the right figure. The EPC is made up of several components: The Mobility Management Entity (MME), the Serving Gateway (S-GW) and the Packet Data Network Gateway (P-GW). The evolved ULTRAN is a radio access network that is made up of base stations. Scheduling, dynamic resource allocation, measurement configuration and prevision, radio admission control, connection mobility control, intercell radio resource management, and other operations are included [53].

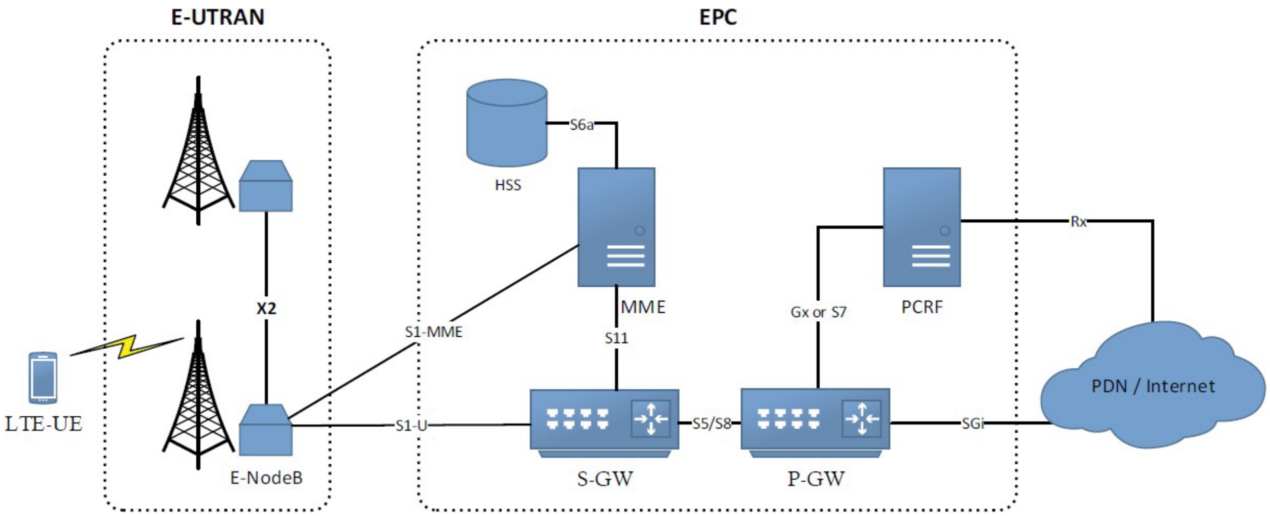


Figure 2.14: LTE network architecture (adapted from [106])

2.3.2.6 - Fifth generation 5G mobile communication system (a glance of 6G)

The 5G technology is divided into three parts: Core, Air interface and Terminals. Wireless access technology will continue to develop in a multi-user environment with a large number of terminals, which means that 5G networks will be able to support a large number of users at high speeds. Table 2.3 illustrate how different technological trends will impact the 5G revolution.

The advancements in communication technology have seen a huge leap from 1G to 4G, then LTE-A to 5G. The changes are shown in Table 2.3. We can see that LTE will begin operating below the 6.5-GHz frequency range by 2020. Most human work will be automated and taken over by intelligent robots who will require ultra-fast internet with minimal latency.

As the preferred technology, 5G is projected to support and simplify the use of TI applications and data transfer across the user equipment (UE), radio access network (RAN), and core network. According to the 3GPP organization technical standard (2017), this is due to the flexibility of 5G architecture and its elements, which are represented in Figure 2.15. The 5G architecture is designed to be flat, with the control plane isolated from the user plane, for a variety of reasons, including practicality and the ability to adjust functionality to any type of service need, and to facilitate scaling. The 5G core network is built around modular functions that generate services, with all modules communicating with one another. This is why the 5G core network allows for the virtualization of network functions and the creation of network slicing as soon as a new service appears [54, 55, and 56].

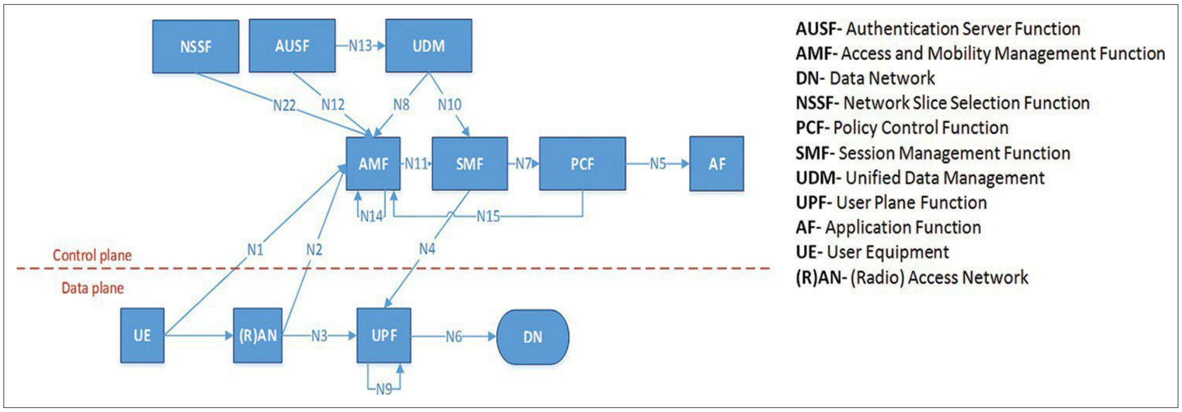


Figure 2.15: Fifth-generation architecture [55]

Features	1G	2G	3G	4G	5G	6G (supposed)
Period	1980-1990	1990-2000	2000-2010	2010-2020	2020-2030	2030-2040
Round trip Latency	>1000 ms	300-1000 ms	100-500 ms	< 20 ms	< 1 ms	< 0.1 ms
Throughput	14.4 Kbps	172 Kbps	14.4 Mbps	1 Gbps	10 Gbps	-
Maximum frequency	894 MHz	1900 MHz	2100 MHz	6 GHz	90 GHz	10 THz
Service level	Voice	Text	Picture	Video	3D VR/AR	Tactile
Standards	MTS, AMPS, IMTS, PTT	GSM, IS-95, CDMA, EDGE	UMTS, WCDMA,IMT2000, CDMA2000,TD-SCDMA	WiMAX, LTE, LTE-A	5G NR, WWWW	–
Multiplexing	FDMA	FDMA, TDMA	CDMA	OFDMA	OFDMA	Smart OFDMA Plus, IM
Architecture	SISO	SISO	SISO	MIMO	Massive MIMO	Intelligent surface
Core network	PSTN	PSTN	Packet N/W	Internet	Internet, IoT	IoE
Highlight	Mobility	Digitization	Internet	Real-time Streaming	Extremely high rate	Security, secrecy, privacy

Table 2.3: Detailed comparisons from 1G to 6G communications

2.3.2.7 - Towards the Internet's next large twist of development: The Tactile Internet

Wireless communication has already been shaping the globe in an unprecedented way. It has become an indispensable element of present-day life. Since the most people around the world are connected wirelessly, wireless communication continues to impact every aspect of modern life, including economy, health, education, politics, entertainment, and logistics, among other areas. Until date, wireless communication has only been used for content delivery (voice telephony, video streaming, e-mails, text messaging, and file sharing) and other monitoring applications (information gathering). Wireless technologies have shifted their focus in recent years to provide pervasive connectivity for machines and equipments, resulting in the Internet of Things (IoT). The exponential growth of electronic advancements has resulted in an exponential increase in the volume and size of content to be sent. The Tactile Internet is the next step, which is a future communication system that allows for real-time communication of human sense of touch and actuation [3].

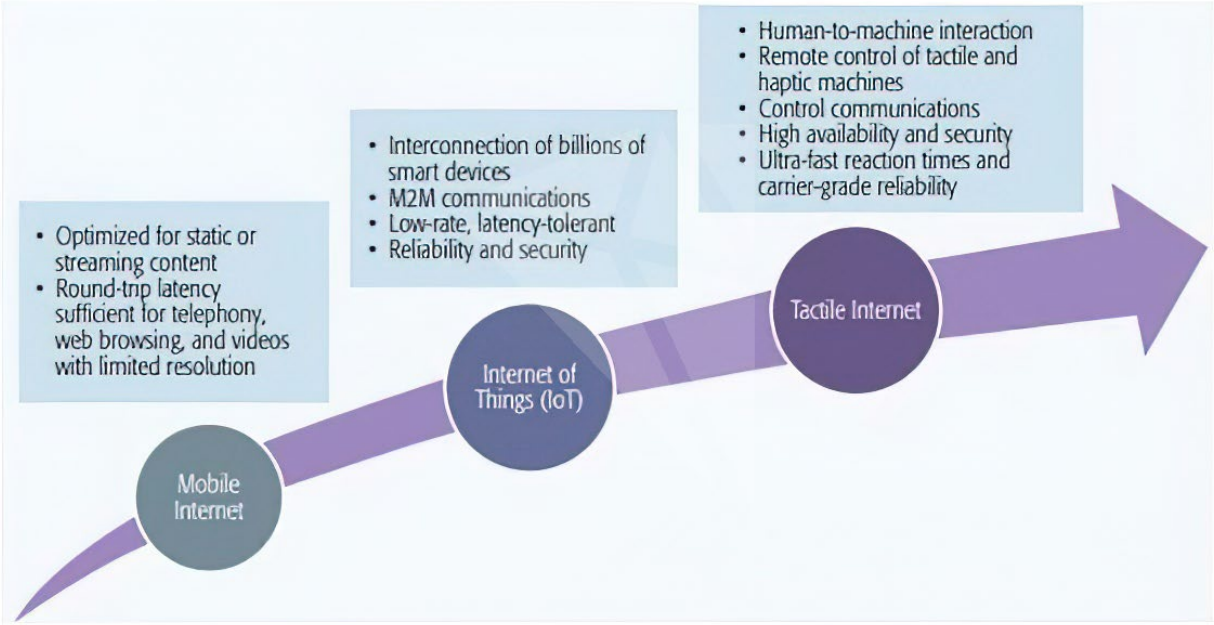


Figure 2.16: Revolutionary leap of the Tactile Internet [177]

The IEEE P1918.1 coined and defined the term "Tactile Internet" 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” [57].

The Tactile Internet (TI) is intended to produce a "paradigm shift" in networks that previously just delivered content. TI will now be able to deliver whole skill sets [57].

Technical Requirements

Below are the most important requirements for the Tactile Internet. These requirements are needed to improve the Quality of Experience for the user [3]:

Ultra-Responsive Connectivity: The Tactile Internet necessitates ultra-responsive network connectivity. Tactile users will feel cyber-sickness if real-time transmission is used, which is caused by conflicts between the visual, vestibular, and proprioceptive sensory systems.

Ultra-Reliable Connectivity: The possibility of guaranteeing a necessary function/performance under specified conditions for a particular time frame is referred to as reliability.

Security and Privacy: For tactile applications, new coding methods must be designed that allow only authorized receivers to decode a secure message.

Edge Intelligence: The fundamental barrier imposed by the finite speed of light must be solved through the Tactile Internet. As a result, intelligence at the network's edge (Mobile Edge Cloud-MEC) is required to enable proactive caching.

Tactile Internet Basic Architecture And Its Components

The Tactile Internet, in contrast to traditional Internet designs, provides a means for transmitting touch, control, and sensing/actuation information, allowing humans and machines to interact with their surroundings in real time. Because of the wide range of Tactile Internet applications, creating a new universal infrastructure is difficult. A master domain, a network domain, and a slave domain are the three domains that make up tactile Internet architecture [58].

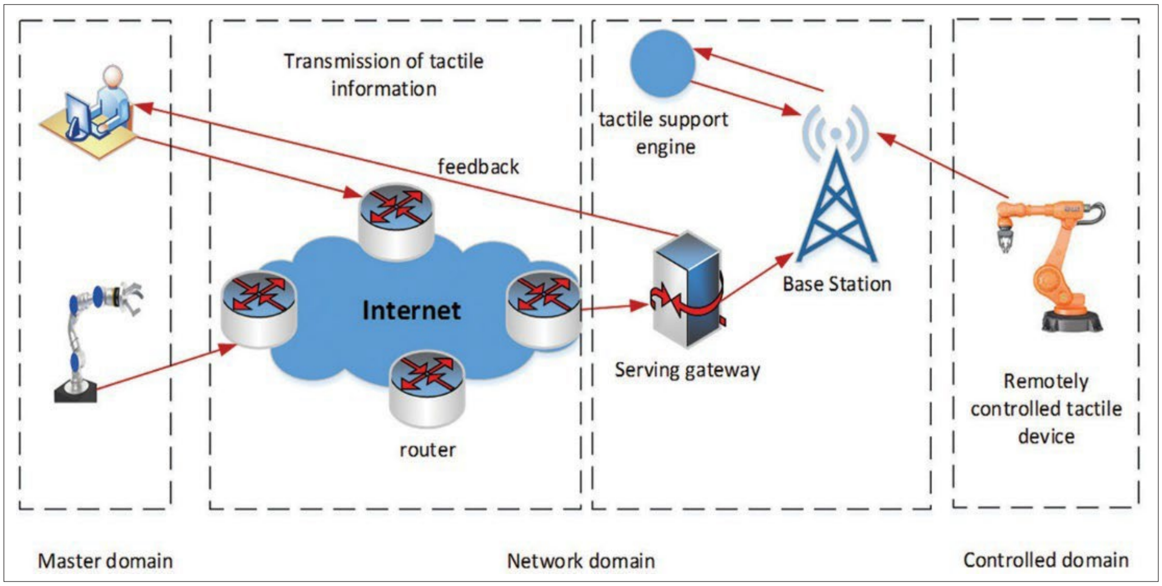


Figure 2.17: Tactile Internet Structure (adapted from [176])

Master Domain

The master domain usually consists of a human/machine controller (operator). Also, it consists of a human system interface (HSI) [59]. The HIS (intelligent robot) converts the human input to tactile input and let the user manipulate and control through the exchange of haptic data, by the use of proper coding, such as tactile coding. Furthermore, its principle role is to direct and control the slave domain's operations and therefore, allows a similar functionality for remote interaction. The master domain issues directives to the controlled domain, such as velocity, and receives a reaction in the form of force.

Network Domain

The network domain creates a path for the communication between the master and slave domains, and so connects the human to the remote environment kinesthetically (i.e. physically). Research challenges include innovative physical layer transmission techniques, enhanced wireless access, and fundamental networking protocols. Once achieved, it will open up new possibilities for operators, content providers, and other service chain participants. The network domain for Tactile Internet demands ultra-reliable, ultra-responsive, and secure connectivity for real-time haptic communication. As a result, TI's 5G communication architecture can meet these high standards. To address the key criteria for TI, 5G communication architecture's core network (CN) and radio access network (RAN) components are required. The high-availability internet is another aspect of TI that enables manufacturers to develop societal and vital applications. The following aspects make up the TI architecture's network domain:

(a) Router: A router is a data packet analyzer that runs on a network. It determines the most efficient path between the source and destination nodes. The router is utilized in TI architecture to carry audio-video and haptic data.

(b) Packet gateway (PGW): A packet gateway (PGW) is a network function that serves as an interface between LTE and other packet data networks.

(c) Serving gateway (SGW): Its primary job is to route data packets and to keep track of user equipment's IP barrier information (UEs). It serves as a checkpoint between PGW and the mobility management entity (MME). The MME is used for network security, such as user authentication and permission. It satisfies TI's fundamental characteristic of secure communication.

(d) Base station: A base station is a radio transceiver that serves as a central hub for wireless devices to connect to the network via antenna. The communication is carried by radio frequency, and the coverage area is referred to as a cell.

(e) Tactile support engine: This network domain component contains artificial intelligence (AI) algorithms for anticipating haptic experiences, such as an increase or change in movement on one end and a corresponding change in force feedback on the other.

Slave Domain

The slave domain is made up of a teleoperator (controlled robots, sensors and actuators, etc.). By passing various control signals, it is directly operated or controlled by the human operator in the master domain. The teleoperator's job is to communicate with distant things. It includes wearable-controlled gadgets, which are likewise led by the master domain.

Tactile Internet reference architecture IEEE P1918.1

Aijaz et al. [62] suggested the reference architecture for TI. This architecture's design principles are as follows: (a) create a universal standard architecture for all smart TI applications, (b) connect to LAN and WAN networks using both wired and wireless connections, (c) separate the control and data planes, (d) support interaction with third-party services, and (e) use MEC to bring computing resources closer to the network's edge. As shown in Figure 2.18, the IEEE standard P1918.1 is a reference architecture with two tactile edges and a network domain. The master (controller) and slave (controlled) domains are represented by the two tactile edges of this architecture. The master domain of the reference architecture, like standard architecture, consists of a human operator or a machine controller. The controlled domain is made up of items that are controlled remotely by the master domain's human controller. Similarly, in full-duplex mode, the network domain connects the tactile edges for bidirectional information transfer.

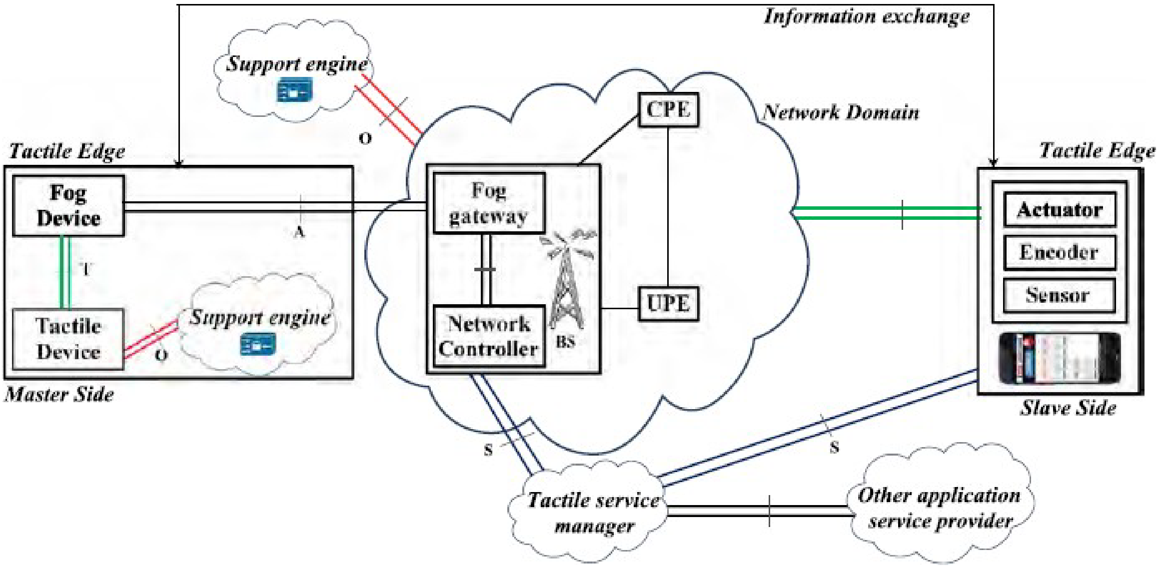


Figure 2.18: IEEE P1918.1 reference model in which the network controller and the gateway are part of the tactile

edge [62]

Challenges

Designing Tactile Internet network and realizing it, meets a few challenges since the current networks don’t have sufficient features in order to support real-time communications. The main challenge is the “1ms round trip (end-to-end) latency” also known as “the real-time challenge”. In contrast to user plane latency, round trip latency is defined as the time between the transmission of a small data packet from the transmitter's application layer and the reception of the data by the receiver's application layer, including any response feedback provided by the communication process (as shown in Figure 2.19). Hence, the round-trip latency is proportional to the number of network nodes involved in the communication. To reduce round-trip latency and meet the 1ms delay requirement, the number of network nodes involved in the communication process should be reduced and the nodes should be brought as close to the user device as possible. This can be achieved by Network Coding and Software Defined Networking which is our proposed architecture [58].

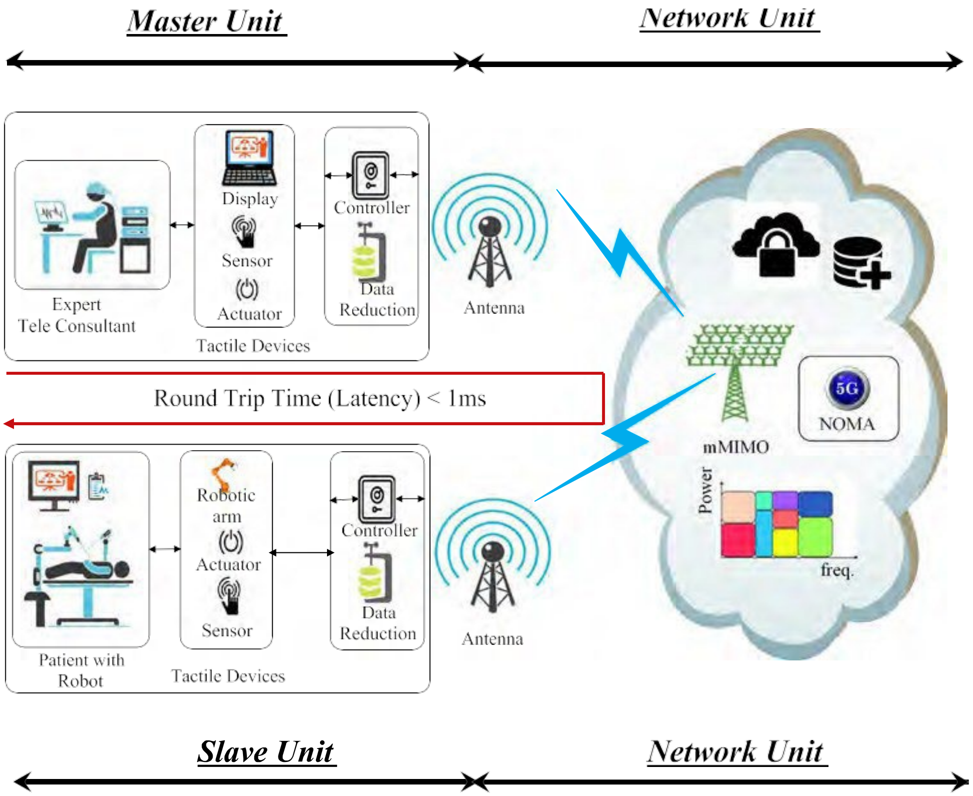


Figure 2.19: Latency goals to realize the Tactile Internet: Basic architecture of TI (adapted from [60, 6])

Moreover, communication, control, touch, and sensing capabilities must all be integrated into a shared real-time system for the tactile Internet to be realized. Despite the usage of virtualization, softwarization, and MEC to achieve low latency requirements, the tactile Internet is still in its infancy, and further research is needed to overcome a number of outstanding technological hurdles, such as physical layer challenges. To reduce signaling overhead and air interface latency, other challenges must be considered, such as Control and User Plane Separation approaches, intelligent control plane, robust modulation techniques, and effective waveform selection methods. Because they can lower end-to-end latency, scalable routing approaches and adaptive network coding schemes are also worth researching further.

Applications (Use Cases)

In the following, we look briefly at three different Tactile Internet use cases (or applications): tele-robotic surgery, autonomous driving, and remote phobia treatment.

Tele Robotic Surgery

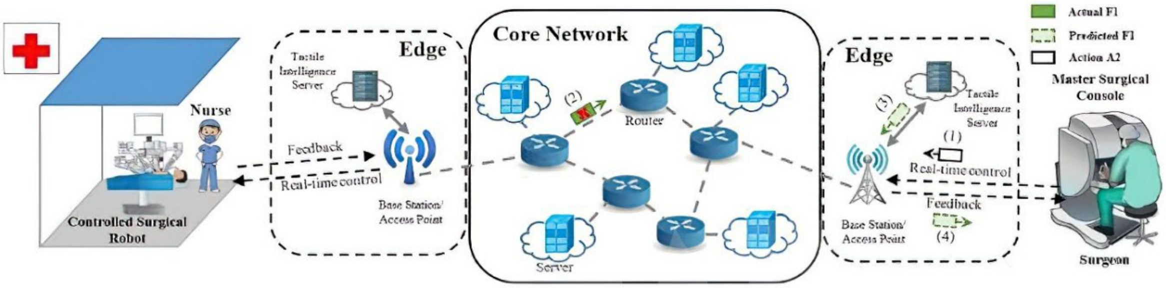
Surgery will be available practically anywhere, regardless of where surgeons and patients are located, thanks to remote robotic (or tele-robotic) surgery. This has a number of potential benefits for human society, including decreasing the hazards and delays involved with long- distance patient transport and allowing patients in underserved areas to have surgery. In a nutshell, it will facilitate the spread of advanced surgical capabilities [169, 170]. Figure 2.20.a depicts a Tactile Internet system based on 5G for remote robotic surgery that is built on an edge architecture.

Autonomous Driving

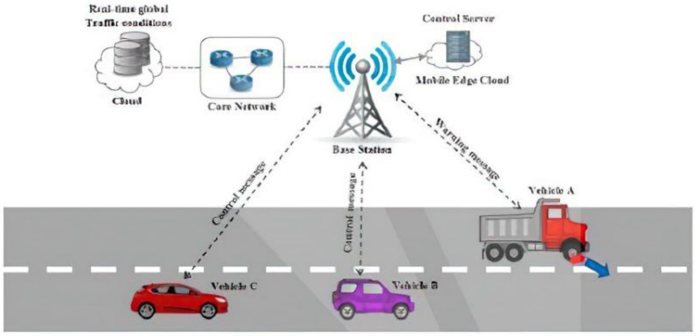
Another use that the Tactile Internet has the potential to fulfill is autonomous driving. In the future, it is predicted to play a vital role in reducing accidents, traffic congestion, and greenhouse gas emissions [171]. A Tactile Internet system for autonomous driving use scenarios is shown in Figure 2.20.b.

Tele VR Phobia Treatment

Virtual reality (VR) has recently been shown to be an effective treatment for phobias [172, 173, and 174]. Therapists might use this technique to treat phobic patients by gradually and systematically exposing them to their dreaded objects (such as snakes or spiders) in a virtual reality environment without putting them in danger. Unlike previous phobia treatment methods, therapists can fully manage the feared stimuli by modifying the size and movement of the feared objects in virtual environments dependent on their patient's fear level [173, 174]. Traditional VR phobia treatment will gain more benefits through the Tactile Internet. It will enable therapists to treat their phobic patients wherever they are and at any time. A Tactile Internet system for a tele-VR phobia treatment use case is shown in Figure 2.20.c.



(a) Remote Robotic Surgery



(b) Autonomous Driving

(c) Tele-VR phobia treatment

Figure 2.20: Tactile Internet use cases deployment in real-time applications: (a) A knot-tying task with Tele-Robotic surgery, (b) Collision avoidance with autonomous driving, and (c) Spider phobias treatment using tele-VR therapy [175]

2.3.3 - Beyond LTE Networks: Software Defined Networking (SDN)

In recent years, the expression "software-defined networking" (SDN) has been coined. The notion of SDN, on the other hand, has been emerging since 1996, motivated by a desire supply user-controlled forwarding management in network nodes [63].

Adaptability is a repetitive obstacle for traditional networks. In fact, these latter frequently function admirably with restrictive provisioning programming and cannot be immediately adjusted as required. SDN is a new approach that provides efficient solutions for achieving network flexibility and efficiency. SDN is characterized by “the decoupling of control and data planes” in the network making them, linked through the OpenFlow interface protocol.

After advancement of communication technology for many decades, the Internet has now turn out to be the largest international computer network worldwide. With new protocols and standards added to refine the performance of the internet, network behaviors grow into very complicated, and it is challenging to anticipate them. At the same time, the existing Internet infrastructure seriously curbs the net-work innovation and its reformatting. For instance, traditional networking is established in fixed-work networks i.e., a couple of switches and routers. These devices each have certain capacities that work well together and bolster the network. On the off chance that the network’s capacities are actualized as hardware constructs, at that point its speed is normally reinforced. Adaptability is a repetitive obstacle for traditional networks. Not many Application Programming interfaces (APIs) are uncovered for provisioning and most switching hardware and software are proprietary. Traditional networks frequently function admirably with restrictive pro- visioning programming, yet this product cannot be immediately adjusted as required. Software-defined Networks (SDN) is characterized by "the decoupling of control and packet- forwarding planes in the network" [64, 65, 66, and 67]. It empowers the network to legitimately associate with applications through application programming interfaces (APIs), supporting application execution and security, and making an adaptable, unique network design that can be changed as required. Apparently, the most regularly utilized method for application deployment, SDN is utilized by enterprises to send their applications quicker while likewise cutting the deployment and operating expenses. IT heads utilizing SDN can oversee and provision their network services from an incorporated point. A network model that yields programmatic management and control, and network asset optimization, SDN applies open APIs to help keep up network control. This network control is made when SDN decouples the network design and traffic engineering, isolating them from their central network infrastructure. This splitting permits the utilization of OpenFlow and other open protocols. These open protocols can access network switches and routers that regularly utilize exclusive and generally closed firmware by applying globally aware software control at the network's edge. SDN helps clients virtualize their hardware and attempts to make a computer network by separating the system [68] into the accompanying separate planes: The control plane offers the performance and fault management of NetFlow similar to protocols, is much of the time utilized for managing devices designs that are remotely associated with the software-defined network. The data plane advances traffic to its ideal destination. Before traffic arrives at the data plane, the control plane directs what path streams it will take by utilizing the flow control—when a network administrator works with the software-defined network and manages the network. At the point when it was first deployed by huge enterprises, for example, Google and Amazon, SDN helped them make adaptable server farms, encourage network resources and new server development, and decrease the workload for IT directors. SDN streamlined the efficiency of the up-scaling procedure for these huge organizations and immediately drew the consideration of other huge organizations that quickly embraced SDN to improve their up-scaling effectiveness.

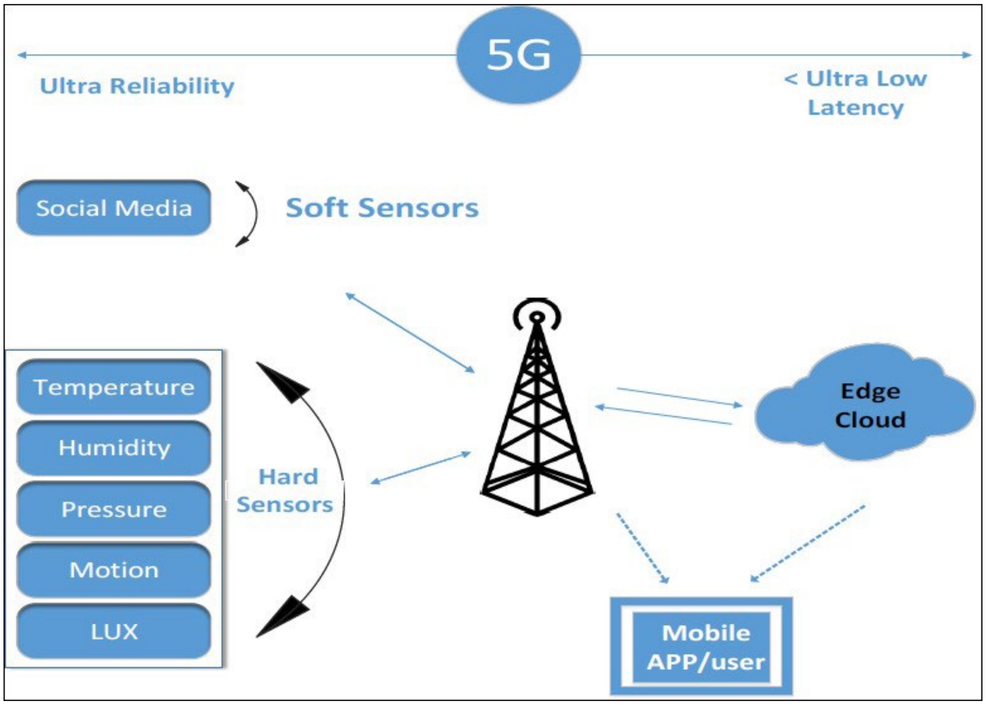


Figure 2.21: Modern IoT architecture

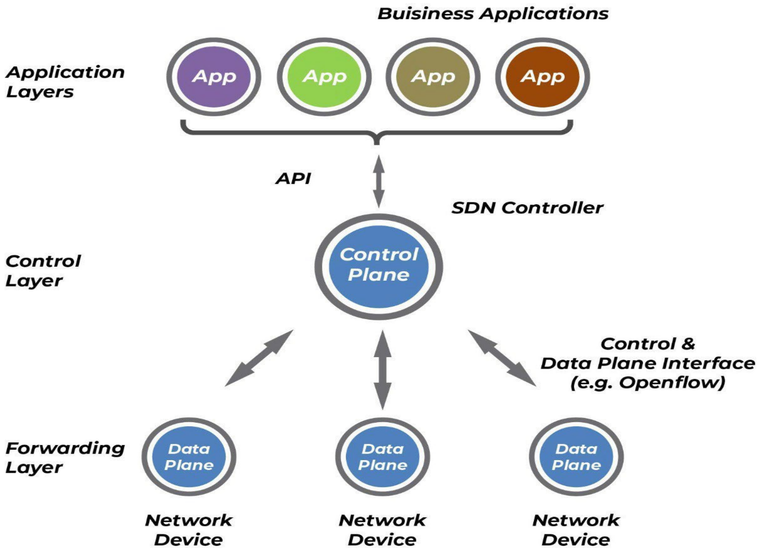


Figure 2.22: SDN architecture

On the other hand, Internet of Things IoT includes broadening web availability beyond standard devices, for example, work areas, workstations, cell phones, and tablets, to any scope non-web enabled physical devices and regular items. Embedded with technology, these devices can convey and communicate over the web, and they can be remotely observed and controlled. As illustrated in Figure 2.21, hard sensors are sensors which are physical, hardware-based, like fire sensors, ambient light sensors, humidity, and cameras. Moreover, physical sensors can be connected to the user. These include wearables and personal sensory devices, gathering mainly physiological data, and providing valuable perceptions on health and well-being. Hard sensors can also be ambient sensors, supplying data on the user's environment at any given time. Moreover, continuous tracking entails data gathered by soft sensors. Soft sensors collect data mainly from Social cloud media (SNs) such as Facebook, Instagram, YouTube, Twitter, LinkedIn, etc. They are referred to as soft sensors because they are software-based, where information is entered into the platform by humans. Both IoT and SNs provide high amounts of sensory data and varied views on the human's state of health and well-being [1, 69, and 70]. The raw data from the sensors is sent to an IoT gateway, which is installed in the user's home. The gateway will send via the promising regular network or ultimately using the ultra-reliable with ultra-low latency 5th generation of mobile communication (5G) that sensory information to the cloud server. The server will do data analytics from the received raw data and send the message to the user's mobile app. The preceding scenario depicts the most rigorous and extreme example of IoT deployment. Traditionally, the IoT communications comprise nearly all the communication technologies of wireless communications and wired communications. As for wireless communication technology, there are GSM, CDMA, LTE, Wi-Fi, RFID, Bluetooth, and ZigBee. The use of some kind of control architecture is utmost required to ensure a smooth QoS for IoT. Nowadays, associated devices are a part of a situation wherein each device converse with other related devices in a domain to robotize home and industrial tasks, and to impart usable sensor data to clients, organizations, and other interested parties. IoT devices are intended to be deployed for people at home, in the industry, and the manufacturing domain. The devices can be classified into three fundamental gatherings: consumer, enterprise, and industrial. User connected devices include smart TVs, speakers, toys, wearables, and well-informed machines. Smart meters, business security frameworks, and smart city technologies. For example, those used to monitor traffic and climate conditions are instances of industrial and enterprise IoT devices. Different technologies, including air conditioning, thermostats, smart lighting and smart security, enterprise and industrial uses. In a smart home, for instance, a user arrives home, and his car communicates with the garage to open the entryway. Once inside, the indoor regulator is as of now acclimated to his preferred temperature, and the lighting is set to a lower force and his picked color for relaxation, as his pacemaker information indicates it has been an unpleasant day. In the enterprise, smart sensors situated in a gathering room can enable a worker to find and schedule an accessible room for a meeting, guaranteeing the best possible room type, size, and highlights are available. When meeting participants go into the room, the temperature will change as indicated by the occupancy, and the lights will diminish as the fitting PowerPoint loads on the screen and the speaker starts his presentation. One of this thesis' main contribution is to investigate the applicability of existing network technologies, topologies, and research in integrating Software Defined Networks implemented via edge computing to the Digital Twin and IoT architectures.

2.3.3.1 - Software-Defined IOT: An overview

With the development of communication technologies, the Internet of Things has driven a revolution of new network architecture, from industrial to military applications. This revolution includes many aspects such as healthcare, home automation, earthquake warning, traffic control, and industrial processing monitoring. In terms of different use cases, dedicated platforms and applications are built by different providers. As a result, there is a lot of redundancy in IoT devices, data, operations, and system management [71]. Generally speaking, an IoT network is composed of a group of sensor and actuator networks, as well as end-users' SNs and their devices, which work as the edge network. Mean- while, the edge network is supported by some gateways and access points (Access Network). Datacenter network and core network also play an important role in IoT network. Besides, SDN technologies can be used in the different types of network in terms of use cases. SDN-based schemes for efficient data collection and network flow monitoring in edge networks have lots of applications in IoT [72].

Data aggregation: In OpenFlow-based flows placement, the SDN controller plays a key role in the network, leveraging the global view of the entire network. At this point, flows can be monitored and analyzed for making improved decisions. An IoT network comprises heterogeneous devices [73]. With SDN, it becomes possible to control all the devices in a uniform pattern.

Network monitoring: SDN can provide a global view of the entire network. With this property, the network monitoring in SDN can be achieved in two ways: probing by the controller and reporting from switches when changes are detected in the network. For the probing method, the SDN controller will send probe messages to the switches and routers to get statistics from them periodically. It is proved that OPEX is greatly improved in a larger network. On the other hand, if we rely on switches to send network statistics actively, overhead could drop, while accuracy is compromised. Therefore, we notice that there is a tradeoff between control over- head and accuracy.

A - SD- IOT, Access Network

A.1 - Access-Core Integration by Simplifying Network Architecture

In the current IoT network, tons of devices are connected and have communication tasks. The access network will face a major strain in the near future. Therefore, the integration of a heterogeneous access network into a single platform will facilitate seamless data exchange among multiple devices. Active remote node (ARN) [74] will play a crucial interface between the end-users and backhaul network. ARN is responsible for short-range communication, wireless mainly. For long-range passive optical networks (PONs), it works in the backhaul network to provide long-range connectivity. With SDN, service providers will experience conveniences such as dynamic bandwidth allocation, service differentiation, network monitoring, and dynamic spectrum management.

A.2 - Pub - Sub - Based Architecture

Pub-sub architecture provides more scalability in a dynamic network topology. In this architecture, source nodes will update messages without detailed information of the destination nodes. Besides, the destination nodes (subscribers) also express their interest in receiving a different message without details of source nodes (publishers). This will ensure the one aspect of security in IoT networks since it can dramatically reduce the overhead of communication establishment between IoT devices. A pub-sub SDN architecture can enable scalable and distribution services [75]. An abstraction layer is proposed, which is independent of specific networking protocol and technology. Therefore, a dedicated application can be dynamically deployed.

A.3 - SDN based Mobile or Optical Access Network

To apply SDN in an optical access network or in a mobile communication infrastructure such as 4g or LTE-A, several aspects need to be taken into consideration. Users can provide feedback to network service providers and the latter will use the information to make adequate decisions to improve the QoS of a network. With this mechanism, the SDN controller will use per-flow analysis to accordingly explore the optimum path for data forwarding, within QoS concerns.

B - SD- IOT, Core Network

B.1 - Adequate Security Mechanism at Core Network

Each enterprise network puts security issues at a high priority. In general, distributed and centralized solutions are two common architecture. The centralized security uses a network intrusion detection system (NIDS) at the core network. The performance is not satisfying in some aspects. For instance, additional dedicated middleware is required, which increases the overhead; besides, a network operator has only limited views of the network since it is a traditional network architecture, which means the host-band solution approaches are OS- specific and this is likely to lead to different contention between solutions [76].

As a result, SDN should be considered as an alternative approach at the core network to achieve different KPIs of a network.

B.2 - Adequate Network Traffic Distribution

As the presence of heterogeneous devices in IoT, routing requests should be handled properly for different application- specific use cases to fulfilling the user requirement. Traffic should be distributed through redirecting application-specific requests when they are received within the intermediate nodes while minimizing the associated cost, network load, and delay.

C - SD- IOT: Data Center Network

C.1 - Efficient Flow Handling

In the data center network there are two types of flows, long-lived and short-lived, which are also known as the elephant-and mice-flows respectively. It is necessary to handle these two flows efficiently without disrupting the network performance. SDN can help with the issue.

C.2 - Traffic - Aware NFV Deployment

Virtual Machine (VM) is the core computing entity in data center networks. With SDN, the controller has a global view of all the traffic, and monitoring is possible for each VM, while these VMs are running IoT analyzing application in the data center. This will ensure scalability in SD-IoT as well while meeting the best practice of Network Function virtualization (NFV). Therefore, VMs must be deployed dynamically and efficiently, including placement problems and resource allocation problems.

C.3 - Energy-Efficient Data Center Networking

Datacenter network accumulates thousands of computing nodes together and the energy consumption is a great concern for each DCN deployment scenario. To reduce the consumption issue, properly utilized resource allocation policies should be applied in the deployment mechanism. Consequently, adequate techniques need to be proposed for energy- efficient data center networking.

C.4 - Over-and-Under-Subscription of Services

Customers are always tending to subscribe more resources in higher priority to meet their real-time requirement. Naturally, the real-time resource is far more expensive. As a result, some data centers are likely over-and underutilized [77] due to the specialized, real-time service requests especially in IoT application requests, leveraging SDN-based dynamic request mapping technique to distribute the requests among data centers, and load balancing.

C.5 - Seamless Mobility of VMs

Migration of VMs in data centers is always challenging when it is between different DCN vendors. Providing seamless connectivity is a key aspect of IoT. Which needs to be achieved in DCN by creating requests by VMs or containers. SDN and NFV are good examples to provide efficient service migration solutions and meet the requirement of QoS and service-level agreement.

D - SD- IOT: A Model

IoT has been emerged as a special skeleton/model of wireless sensor networks (WSNs). It is worth noting that the large-scale deployment of WSNs is difficult and poses some problems; therefore operators need special adaptation procedures when they use specific applications that require flexibility and particular management. To tackle these problems, the thinking of integrating SDN to WSNs, is introduced and a new SD-IoT model is born, Figure 2.23.

The two layers of SDN (control plane and data plane) communicate via the Sensor-based OpenFlow (SOF) communication protocol. The sensors transmit data packets according to the flow table. One or more network controllers make up the control plane (s). It is possible to achieve network intelligence as well as network control (like routing and QoS control). Users can achieve the programmability of the WSN by running the major flow table by SOF in this configuration. The following are some of the features of SD-IoT: (1) Multifunctionality: SD- IoT may support multiple plug-and-play applications, removing the sensor's reliance on the application. The network's logic functions are stored in the control plane. (2) Flexibility: Changing the entire approach in the network setting, is a simple task for SD-IoT. This helps network operators and network equipment manufacturers, to escape from incompatible local strategies. (3) Manageability: The network management systems only requires open API provisioned by the control plane. This is same as the means of adding new applications, without necessarily tweaking the actual primary code. Adaptability in the network can be accomplished using artificial intelligence-based network controller, thus smart routing and QoS control can be achieved. As illustrated in Figure 2.23, the deployed SD-IoT model is composed of three layers: the physical layer, the control layer, and the application layer.

The OpenFlow protocol is a signaling standard that allows SDN controller SDNC and OpenFlow switches to communicate. Through a protected OpenFlow channel, each OpenFlow node talks with the SDNC. The instructions determined from the flow table received from the SDNC are used to generate the switches' forwarding tables and packet processing rules [182].

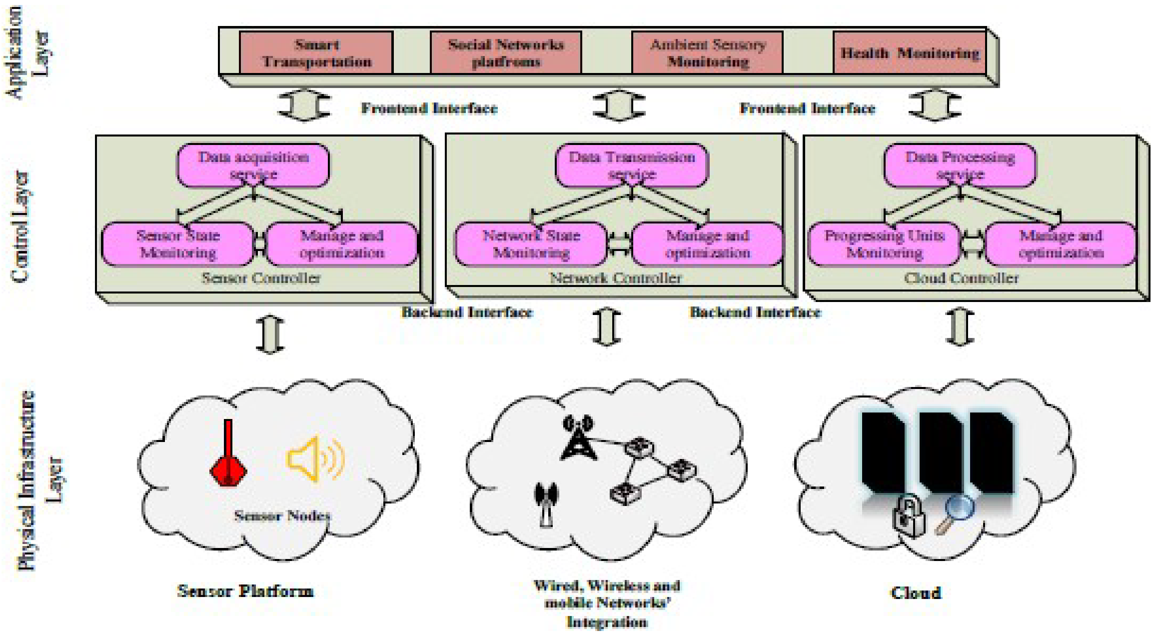


Figure 2.23: Structural Model of Software Defined Internet of Things (SD-IoT)

The advantages of Open Flow are:

- The controller is in charge of how packets are sent.
- Rather than being customizable, make deployed networks programmable.
- Rather than only source/destination MAC/IP, "flows" (traffic types) can be programmed.
- Allows for the combining of switching at multiple network layers.
- It isn't constrained by the platform or governed by protocols.

The physical layer

In this layer, all the assets and hardware devices are placed. These devices will be responsible for the main data communication tasks only without the participation of the controlling process. More specifically, it is composed of a sensor network cluster (SN), database pool cluster (DB). For sensor network clusters, IoT devices (sensors contained) are the main function points. The sensors are responsible for recording the data from the surrounded environments in order to use it in different applications. Agents work as assistants or interfaces to communicate with upper layer devices and controllers. The board sensors will combine the accumulated data from bottom sensors and send them by a bridge or gateway to the SDN controller. On the other hand, database pool cluster provides different types of data storage. As a result, a dedicated database will be created to store IoT device information for further processing and analysis.

The control layer

Same as the SDN architecture, SD-IoT has an SDN controller in this layer. Besides the basic SDN components, it contains the specific IoT controller, which focusing on IoT applications and its data forwarding and processing issues. SD-Storage controller, SD-Security controller are encapsulated in this layer in order to deal with urgent situations. Those controllers form an integrated middleware layer, eastern and western bound interfaces are also integrated to ensure the data communication between controllers. In a wide range system where the system is physically distributed, an edge controller should be considered in this middleware layer to handle all the requests from the bottom and the top.

The application layer

SD-IoT provides a DaaS (Data as a service) application layer. User-applications are generated in this layer to facilitate accessing and acting with the stored data. Similar to SDN, northbound or front-end APIs should be introduced to enable data communication between the upper layers and controllers.

E – The Overall Workflow of the SD- IOT Model

Figure 2.24 presents the overall workflow SD-IoT model at the control layer. A service request is created by an IoT device, or more specifically, a sensor. Pieces of information are generated and it is forwarded to the control layer by gateways and bridges. Before the requests are accepted by the SDN controller or the IoT controller. It needs to pass the authentication investigation handled by Software Defined Security (SDSec). If this process failed, the requests will be discarded, and otherwise, it will be allowed to enter the message queue to wait for further data processing. After the message processing operations are successfully executed. IoT controller will add labels and tags to the request packets to a dedicated receiver. This labeled request will be handled by the SDN controller for further forwarding. A specific flow forwarding algorithm will be applied in the SDN controller. Meanwhile, the SDN controller should coordinate with IoT controller in case of updated policies or information challenges. Besides, it is responsible to release the flow rule to broadcast the final routing and forwarding information to the bottom devices that are in the sensor network cluster. When new flow rules are established, the SDN controller will notify the SD-storage controller, and they will be stored in the DB cluster for further processing if necessary. The process below explains how to connect IoT to an SDN network in a quick and easy way. As previously said, diverse inter- networking scenarios present a variety of obstacles in terms of use cases and format. This is what we'll look at in the parts that follow.

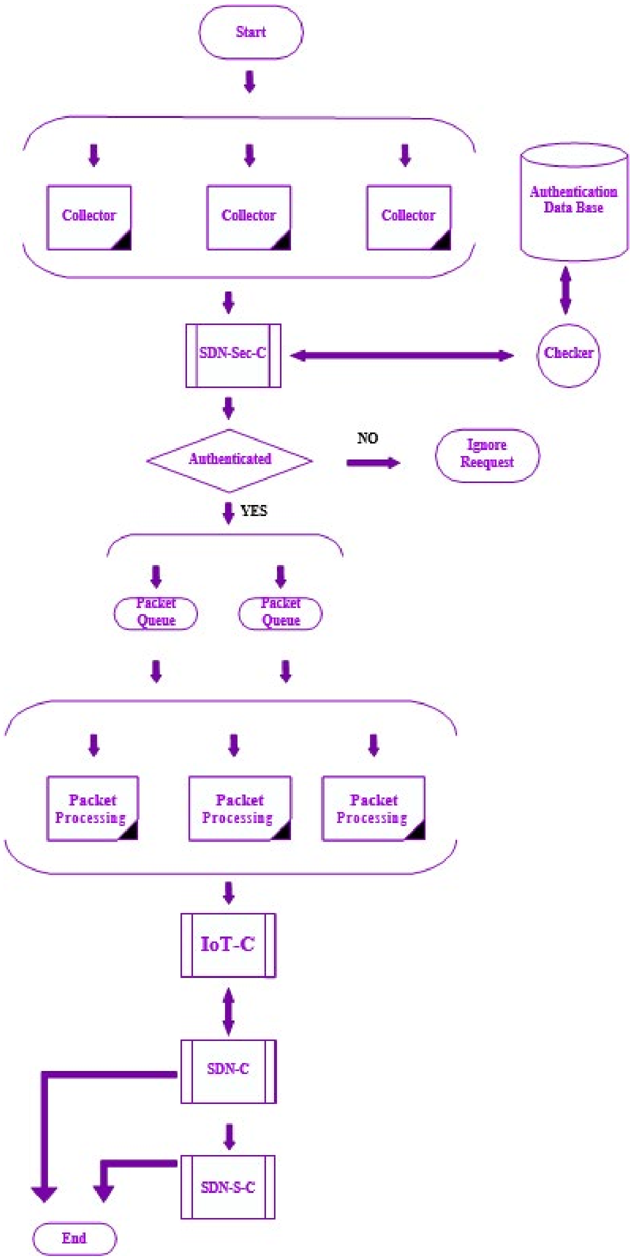


Figure 2.24: The (SD-IoT) process (workflow) for handling service requests from the application layer

2.3.3.2 - SDN based IOT models for delay/bandwidth-sensitive and packet loss- sensitive applications

Again, the vision of the Internet of Things (IoT) is to have smart devices connected over the internet as a backbone infrastructure. The network from smart devices to the IoT platform is made up of many

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communication domains and different technologies are used in inter/intra domain. For example, in the access part (access domain) of the network, a smart device can connect to the IoT gateway using different access technologies like Bluetooth, Zigbee, Wi-Fi, etc. Similarly, the IoT traffic on its path to the IoT platform may go through the optical network, metro network, and even mobile networks like (4G or 5G). Secondly, different IoT applications have different QoS requirements from the network. Software-defined network (SDN) has some tools in its arsenal to cope with the heterogeneity of IoT backbone network and QoS requirements. SDN can utilize its logically centralized control plane to achieve unified control over heterogeneous networks and similarly, the flexibility/programmability feature can be used to monitor the network and make dynamic run time changes in the network to meet the QoS requirements of different IoT applications. Here are many QoS metrics like throughput, bandwidth, jitter, delay, reliability, etc., but in [78], Jin et al. categorized IoT applications in two broad categories:

Delay sensitive IoT applications: These applications require packets to be received by the IoT platform with strict packet delay constraints. They can still work properly if there is some packet loss as long as the non-dropped packets are received within a delay threshold. Examples of these kinds of applications include video surveillance like CCTV infrastructure, smart connected car systems for autonomous driving, real-time health monitoring systems, etc.

Packet loss-sensitive IoT applications unlike delay sensitive applications, packet loss- sensitive applications require packets to be received with no packet loss and can withstand delay. Most of the IoT applications use UDP as a transport protocol that doesn’t provide end to end guarantee, so reliability is implemented at the higher layers but due to the resource- constrained nature of the IoT devices, it’s the responsibility of the network to provide no packet loss to save energy and memory usage on IoT devices. For the packet to be delivered reliably, it must be stored in the buffer of the IoT device so that in case of packet loss, it can be retransmitted but IoT devices have limited buffer space to store packets. Examples of these applications include wireless sensor network for monitoring different environmental parameters and wireless body area network (WBAN) [79].

SDN Based IOT Aware EDGE/CLOUD Architecture For A Bandwidth - Constrained Application

Analyzing raw data collected by IoT devices is a need for any IoT infrastructure to provide useful and concise information to the application's user. In some applications, sensors/actuators collect data in huge amount and require a network to carry this data to the data centers located in the core of the network for analytics. In [80], the authors mentioned the data collected by a connected car system, send to the cloud for analysis is approximately 25 Gb/hour and will exceed this if more sensors are added to the self-driven cars. A connected car has many sensors that may collect the surrounding information, driver's behavior pattern, and telematics to provide vehicle efficiency and passenger safety. Transferring this huge amount of data from edge networks through metro and core networks to datacenters for analytics will cause congestion in the network and will hinder the performance of delay- sensitive applications. Secondly transferring data requires bandwidth with is expensive so there is a need to find an alternative architecture that does not require data sent to the core data center all the time.

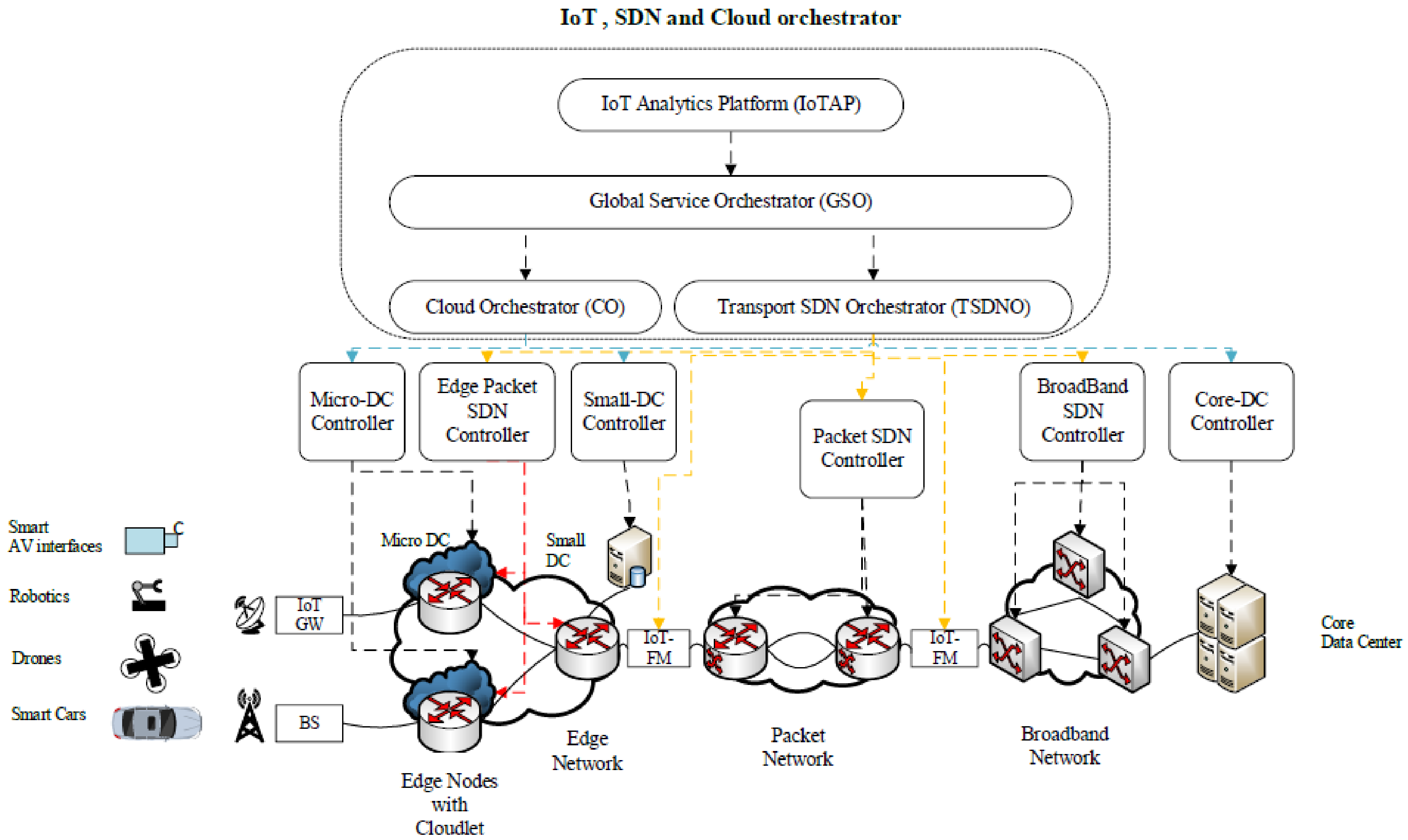


Figure 2.25: United communication design of SDN, IOT, and Cloud Computing

Edge computing in IoT

To solve the processing of large amounts of data at a core data center, the idea of edge computing was introduced whose basic goal is to bring compute and storage resources closer to the edge of the network, which will provide real-time data processing, real-time message response and temporary data storage. The compute and storage resource at the edge network is named as a micro and small datacenter. First analytics is done at the edge side to extract useful information and then this data is sent to the core data center for storage purposes, which will be used by IoT applications. This requires a dynamic distribution of IoT analytics between the core and edge data centers reducing the dependency on the network hence reducing the impact of bandwidth and latency constraints of the network. Authors in [81] survey edge computing in the context of IoT. Dynamic distribution of analytics requires programmability/flexibility, which is a feature of SDN, moreover, there needs to be tight coordination between IoT platform, SDN infrastructure, and cloud/edge infrastructure. The authors in [82, 66] extended the architecture proposed in by providing an SDN-based edge data center (micro and small data center) that uses virtualization of computing and storage for better resource utilization, Figure 2.25. Secondly, they demonstrated the proposed architecture for distributed analytics using CCTV applications and congestion avoidance using a dynamic distribution of analytics. Key features of this architecture are:

- The flexible transition between cloud and edge re- sources based on SDN based (Open Flow) real-time monitoring of the network resources.
- Transferring the request control of edge resource from IoT gateway to a logically central IoT analytics platform.
- Hierarchical implementation of the control plane that integrates the control plane of both different networks and cloud/edge computer.
- Virtual machine-based cloud computes and container-based edge computer.

As shown in Figure 2.25, the connectivity diagram of various components of the unified control and communication architecture is explored. The entire structure can be broken down into three layers:

Infrastructure layer

In the case of static devices, data is gathered from smart things/sensors and aggregated by IoT gateways; in the case of mobile devices, data is collected by base stations (such as smart vehicles or drones and haptic-robotic). The aggregated data is sent to the edge network, which consists of SDN edge switches/routers for data forwarding and micro/small DCs for edge compute and storage. A metro network and an optical fiber wireless network, respectively, are represented by an SDN packet network and a Wi-Fi network, which provide communication between edge networks and core datacenters. IoT flow monitors are installed on transit links between the edge network and the packet network, as well as between the packet network and the broadband channel, to adaptively monitor average bandwidth use.

Control Layer

The Control Layer is made up of many SDN controllers that are organized in a hierarchical way. We have a Micro DC controller, a Small DC controller, and a Core DC controller at the bottom of the hierarchy to offer control plane capabilities for compute and storage resources at the micro DC, small DC, and core DC levels, respectively. We also have multiple SDN controllers (Edge Packet SDN controller, Packet SDN controller, and Broadband SDN controller) that provide packet forwarding control functions for the edge, packet, and optical networks. We have a Cloud Orchestrator (CO) at the second level of hierarchy, which provides a higher-level abstraction for data centers (micro, small, and core) and handles micro, small, and core DC controllers. TSDNO (IoT aware Transport SDN Orchestrator) interfaces to each SDN network controller at the lower level and provides a single transport network operating system. TSDNO interacts with SDN controllers of heterogeneous transport networks using a transport API [83] to deliver end-to-end connectivity services by abstracting higher- level controls from lower-level SDN controllers.

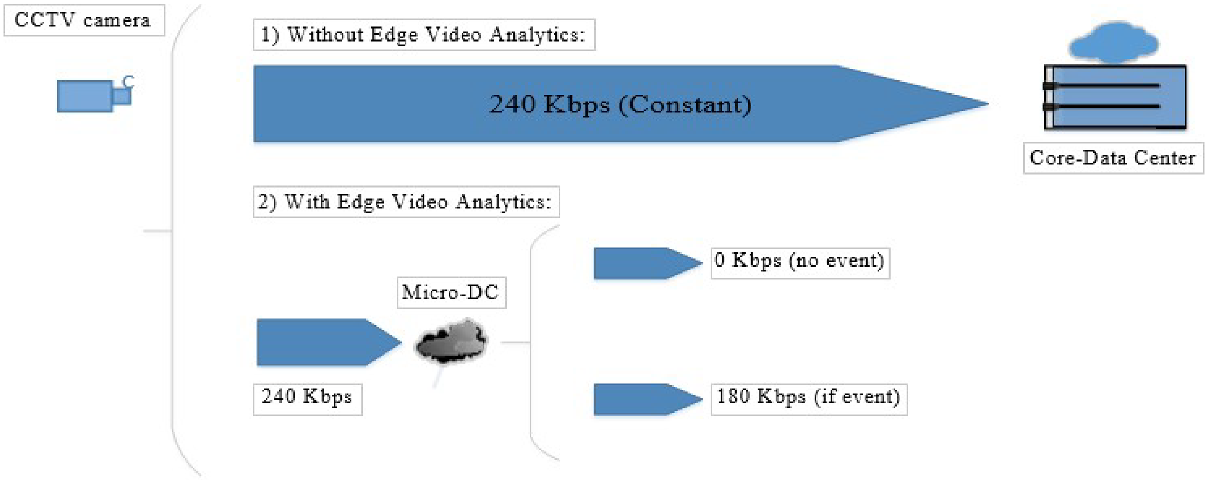


Figure 2.26: Video streaming analytic use case

Another function of TSDNO is to provision tags for IoT flows and subscribe to their real- time periodic information from IoT FM (infrastructure level). Once it detects link congestion on the transit links, it informs the controller higher in hierarchy regarding all the IoT flows passing through the congested link. TSDNO can be viewed as a controller of controllers. At the third layer of hierarchy, an IoT aware global orchestrator (GO) provides global orchestration of end-to-end services. It receives the information regarding bandwidth and latency threshold breaches from TSDNO and forwards the request to the IoT analytics platform (IoTAP) to provision distributed analytic resources at edge, small, or core DC. Upon receiving the global service request from IoTAP, GO decomposes it into two parts. The first one (cloud resource request) is forwarded to CO to instantiate VM at core DC or containers at the edge/small DC. The second part, i.e. end-to-end network and VM connectivity requests are forwarded to TSDNO which further relay this information to lower- level SDN controllers to provision flows. IoTAP sits in the top layer and communicates with IoT applications in the application layer. It decides which IoT application should be distribute

Application Layer

The **Application Layer** which sits on top of the analytic platform providing services to application users, and also provides higher-level instructions to the control layer.

In terms of applications, considering the ontology at the SDN controller can seamlessly link future Tactile Internet applications, such as IoT, to their key performance indicators. As a result, in our recent study [102], we examine the interaction between 5G/Tactile Internet apps and their primary components using ontologies (KPIs). We can modify the classifications of the KPIs and applications by applying the Ontology to the SDN controller, allowing us to infer the most appropriate network type to satisfy the Quality of Service for those applications. Thus, the SDN network controller can benefit from this to dynamically optimize the communication channel necessary for provisioning the required QoS thresholds. We will discuss it in details lately in this thesis.

2.3.4 - Mobile Edge Computing (MEC): Re-Engineering Of Traditional Networks

Another way to improve the cellular network efficiency is to offload network operations to cloud units that are employed at the edge of the cellular system. The idea of Mobile Edge Computing (MEC) was introduced whose basic goal is to bring compute and storage resources closer to the edge of the network. MEC will extremely contribute to the reduction of end to end system latency. In addition, it provides higher system bandwidth, real-time data processing, real-time message response, temporary data storage and reduces the network congestion by providing away for offloading data.

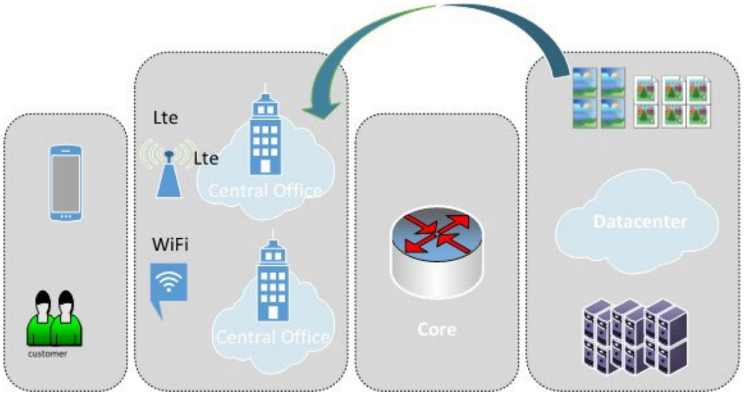


Figure 2.27: Edge Computing Concept

The employment of MEC topology is found on multi-level cloud hypothesis. The multi- level cloud system transitions from centralized to heterogeneous distributed cloud units. Micro-clouds, which have minimal storage and processing capabilities and are connected to each cellular base station, are the initial level of cloud units (eNodeB). Mini-clouds, which are more efficient cloud units with increased processing and storage capacities, are used at the second level. Through a high-speed fiber connection, each Mini-cloud unit links and controls a collection of Micro-cloud devices. The main cloud unit, with powerful storage and processing capabilities focused at the core network, is the final level of cloud units. All Mini-cloud units connected to the core network are connected to the main cloud unit, which connects, regulates, and monitors them. It also serves as a portal to the massive central cloud units that are deployed elsewhere. MEC is characterized by:

- Ultra-low latency.

- Improved bandwidth efficiency by lowering traffic between the edge and the core and so saving bandwidth.

- Local services are services that are available locally and are based on applications.

Powerful management abilities because of the cloud principles, such as, scalability, agility, and flexibility [103, 104].

2.3.5 – Network Function Virtualization (NFV)

The benefits of introducing NFV to the mobile network are numerous, and it contributes to the improvement of the current design. Network functions are separated from routers, firewalls, load balancers, and other dedicated hardware devices by NFV, which allows network services to be housed on virtual machines. Rather than having a dedicated piece of hardware to perform a certain function, software running on a computer or server is used in this fashion. The mobile network operations will be operated as software instances on commodity hardware or datacenters (DC) in this configuration. SDN allows the network layers to be programmable by separating the data and control planes, whereas NFV technology allows for flexible networking service placement. As indicated in Figure 2.28, the goal of NFV is to decouple the network function from the hardware, as established by the European Telecommunications Standard Institute (ETSI) committee [105]. Software is used to implement the decoupled network functions. NFV is a technology that combines virtualization and cloud computing and applies it to telecommunication networks. Virtualized network functions are networking functions that are virtualized (VNF). To construct networking services, these network functions are subsequently interconnected or chained. The VNFs are distributed over one or more virtual machines and use generic hardware instead of vendor-specific hardware, such as off-the-shelf servers. The usage of generic hardware results in substantial cost savings. SDN also provides centralized control and network layer programmability, which NFV can take advantage of. Mobile Service Providers (MSPs) can use SDN and NFV together to make their network services dynamic, allowing them to optimize network resources, boost network agility, launch novel services, and shorten the time between service design and service production. This method also allows for easy network capacity extension and resource sharing between several tenants, as well as support for multi-cell collaborative signal processing.

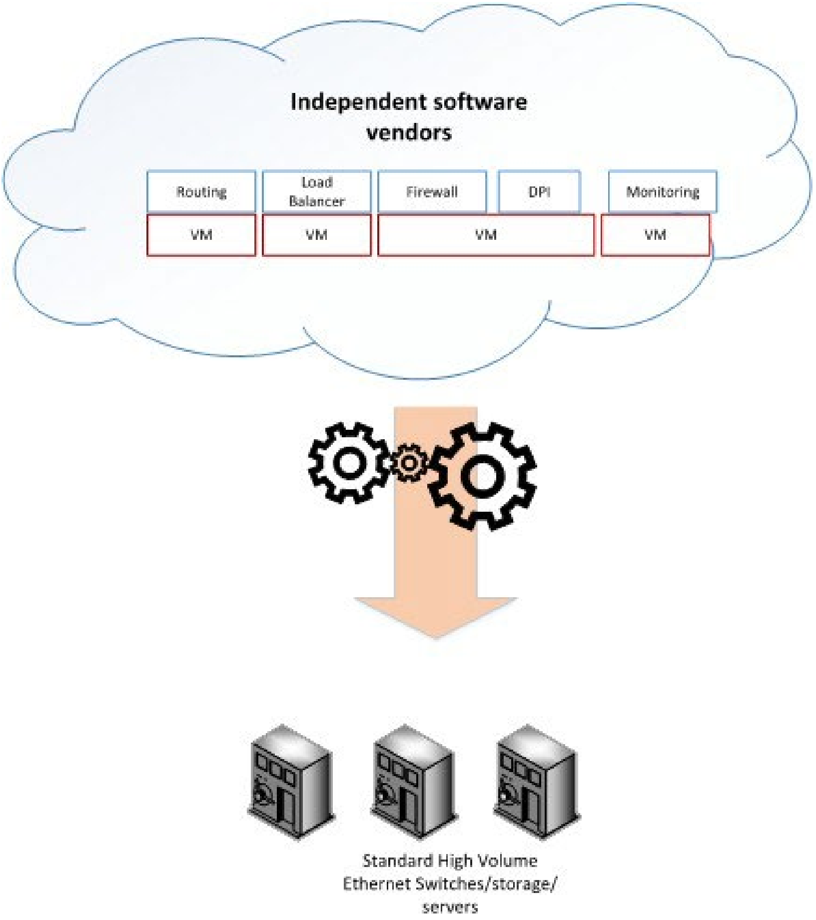


Figure 2.28: Network Function virtualization

2.4 - AI-Based QoS Solution

In a world where Artificial Intelligence integrates with the simplest form of individuality such as a spontaneous vending machine purchase, there emerges the need for an intelligent Human Machine Interface that interacts "Haptically" with the surrounding environment, especially in a world where all "Things" are bound together to form what is now called the "Internet of Things" - IoT. Numerous methods have been proposed to display haptic sensations to the user which are based on mechanical devices known as "haptic interfaces". With traditional media, such as image, audio, and video, haptics – as a new media – plays a prominent role in marking the IoT. The last decade has witnessed a rapid progress in haptics application software development; consequently, the need for a standard for Haptics –precisely Multimedia Haptics - application software modeling is very crucial.

Semantic modeling provides a foundation for interoperability among different systems and applications in the Internet of Things; however, most current research has focused primarily on device and resource modeling, with less attention paid to access and utilization of the information generated by the things. [107]. The concept of things being able to expose standard service interfaces is similar to service oriented computing, and more importantly, it represents a scalable, distributed, and service-oriented means for business services and applications that require context awareness and intelligence to access IoT data and consume data from the physical world [108]. In a philosophical context Ontology is the theory of existence. In information science, an Ontology is a group of representation, formal names, properties, and relationships between concepts and data" [109].

Many applications based on semantic Web technologies have already been seen in IoT research, including the SSN ontology [156] for annotating sensors and sensor networks, Linked Data [157] for sensor data posting [158] and discovery [159], and semantic sensor observation services (SemSoS) [160]. Recent research in [108] and [161] suggests a modeling method in which IoT resources can expose standard service interfaces. This aligns with the Service Oriented Computing philosophy [162] and could provide a scalable, distributed, and service-oriented way to access IoT data. More importantly, traditional service discovery and composition methods can readily access IoT-based services, allowing for the creation of context-aware and personalized services and applications.

Haptics technology has gotten a lot of interest as a way to improve human-computer interaction. In the electronics and computer industries, there is a huge push to create tangible interfaces and devices for the so-called post-PC age. We are already at the start of that era, and we are seeing more and more examples of such interfaces in consumer devices every day.

These devices, despite their modest size and portability, are still recognizable and not necessarily very visually pleasant. The next phase of the post-PC era will see computers and other devices integrated directly into our clothing, for example, making them nearly invisible.

The most difficult component of this journey is still figuring out how to put this tempting technology into practical day-to-day answers. In its new architecture, as proposed by [3], the IoT has five layers. Among these, the “Perception” and the “Processing” layers. Perception is mainly identifying objects and gathering information, hence the need for “sensing data”. Processing is mainly store, analyze and process the information of objects, hence the need for “actuating” and “metadata processing”.

The semantic representation of sensor networks data is an innovative concept that improves search engine quality. What was done before, in the literature, is a step forward towards defining a universal Ontology that makes connections and relationships of the sensor networks units and data. As a result, M. Eid et al. proposed a universal ontology for sensor networks data in [110], a two-layer prototype ontology that uses the IEEE Suggested Upper Merged Ontology (SUMO) as a root definition of general concepts and associations, as well as two sub ontologies: the sensor data sub-ontology (SDO) and the sensor hierarchy sub-ontology (SHO). They used Protégé 2000 to implement this ontology, in addition to the use of RacerPro reasoner for validation, and thus, by computing automatically an inferred class hierarchy based on the description of classes and relationships. Finally, they compared the performance of this approach against traditional syntax-based search, eventually with serving by the role of the RDQL language (RDF Data Query Language) that queries the knowledge base and find out relevant results. Through the use of the universal SUMO, which promotes data interchange, autonomous inference, and extendibility, the performance analysis of their method proved the ability of ontology-based search to improve both precision and recall rates, as well as enhance interoperability between different sensor network domains.

In [111], the authors propose an ontology for modeling Haptics applications, HASM: Haptics Application Software modeling. The two subsystems serve as the foundation for the HASM's design. The Human Haptic System is the first, and it consists of entities connected to touch sensation and perception. The second is the Machine Haptic System, which incorporates haptic device technologies and interfaces that are relevant to the simulation of touch and perception of virtual objects. The BFO (Basic Formal Ontology) framework is used to design HASM, and it follows its hierarchy. The classification of haptics domain entities is based on two criteria: whether the entity is an object or a process, and if the entity belongs to a human or machine haptic system [111]. Using OWL, and SWRL (Semantic Web Rule Language) rules along with the existing knowledge in haptic domain, HASM handles the haptic information flow between the human and the machine haptic sub-system. It will be used as a basis to design effective user interfaces and assist the development of software modeling for haptic devices. Each subsystem's entities are grouped into object classes and process classes after they've been analyzed. The Basic Formal Ontology (BFO) is an upper-level ontology that can be used to support domain ontologies, and the HASM structure is built on it. The Protégé ontology editor in the Web Ontology Language was used to create the ontology (OWL).

To properly develop a haptic rendering algorithm, we need to know the physical, spatial and temporal attributes of haptic devices [112]. Thus, it is needed to acquire existing sensor data. Therefore, in [118], the authors classify the attributes of an HIS (Haptics Interface System) into three categories: “Physical, spatial and temporal”. These attributes constitute a family of new classes (attributes classes), unlike HASM [111] (in which objects and processes classes are the main components).

Moreover, the creation of haptic perceptions at physical and psychological levels is the road to good control of haptic sensations. The main objective is to extract these perceptions and make a decent model that can be fed to an automated system. Ontologies are an important asset to the development of a smart system. However, there are very few proposed ontologies related to smart human perception. This was the idea behind the introducing of an Ontological Representation of Sensory Perception Knowledge, by B. Albert et al., in "A Smart System for Haptic Quality Control" [155]. The authors used a Top Level (high-level) Ontology which is the backbone of a successful structure. The main focus in [155], was on the Semantic Sensor Network (SSN) ontology presented by Compton et al., 2012 [156], where the latter’s introduced the SSN ontology to describe sensors and observations. The SSN ontology is a proposal of relationships between properties, sensors, and observations. This representation involves the integration of haptic perception, as well as automation of the process.

And lastly, we built an Ontology based framework for tactile internet applications QoS KPIs

[102]. In this ontology, we will bind automatically the future generation of Tactile Internet, Digital Twin, and 5G networks applications to their KPIs (Key Performance Indicators). With the help of a Fuzzy Information System (FIS) that we integrated in the ontology, stakeholders are able to infer the most adequate network type to be used for a given application. This ontology is built in Protégé (an OWL Web Ontology Language emulator) with the Suggested Upper Merged Ontology (SUMO) model. The main KPIs are those described further in this thesis (please refer to 3.2) and are the subject of our two works [104] and [102].

2.5 – Summary

In this chapter, we have listed the network requirements to deploy the digital twin architecture with various approaches for the Quality of Service of different multimedia modalities. In addition, we have surveyed existing protocols and frameworks to check their suitability to carry out the transmission and delivery of DT/TI modalities, to end up with the notion of Ontology that helps us to build our proposed framework in this thesis.

Meeting the widely varying communication requirements of each modality, a standardization to annotate and describe each (hence the haptic network), finding the optimal types, methods and rules that are able to accommodate the applicability of the DT/TI systems are briefly the challenges that need to be tackled next in this thesis dissertation.

Chapter 3 - Ontology based framework for Digital Twin and Tactile Internet Applications

Advances in wireless sensor networks have sparked interest in bringing data and capabilities from physical world items into the Internet. The Internet of Things (IoT) is a term that describes the linking of physical objects and their virtual representations on the Internet. IoT has piqued the interest of different scientific communities and industry as one of the basic components of the future Internet. The scope of research and development has broadened significantly in recent years, focusing on IoT infrastructure and architecture, communication protocols for restricted devices, (mobile) sensors and sensor networks, smart things, middleware, security and privacy, and many other topics, rather than the original focus on objects traceability and accessibility using RFID tags. Among these advancements, semantic oriented computing demonstrates its ability to address the difficult problems of heterogeneity and interoperability faced by a huge number of things with varying properties.

Semantic modeling for the IoT domain provides a foundation for interoperability among various systems and applications; nevertheless, present research has primarily focused on IoT resource management, rather than how to access and use data generated by IoT. We provide a descriptive ontology for the DT/TI domain in our study, which integrates and extends prior work in modeling IoT concepts, for the purpose of automatically relating the future Tactile Internet and Digital Twin applications to their KPIs. The ontology helps exploit the synergy of the existing efforts and provides support for crucial tasks such as IoT, TI and DT metadata processing. This can be very beneficial, for instance to the network controller, to dynamically optimize the communication channel needed to satisfy the quality of service to the above systems applications. The ontology is designed to be lightweight in order to promote reuse and support more efficient inference. It is compatible with numerous widely used semantic models in TI, DT, and IoT. The ontology development has been done with the Protégé 4.3.0 ontology editor in the Web Ontology Language (OWL) [165].

3.1 – Design Fundamentals for the description Ontology

In this chapter, we propose an ontology using a knowledge-driven approach, as in [107], with the goal of capturing the majority of the key concepts and their relationships in the TI and the DT domains. The linked data principle is central to the design: isolated concepts from previous studies are linked to one other, as well as external domain ontologies and the open linked data cloud (we can import other domain ontologies into our ontology). The main goal of our design is to strike a balance between being lightweight and complete. In fact, this was the main reason that fueled our decision for choosing the model in [107], apart from the knowledge-driven approach. The following four principles guide the development of the ontology:

(1) Lightweight: prior ontology development experiences demonstrate that a lightweight ontology model that strikes a good balance between expressiveness and inference complexity is more likely to be widely adopted and reused.

(2) Completeness: By integrating and extending current efforts on IoT modeling, we hope to provide a more complete descriptive ontology for the IoT domain. Users of the ontology can take use of integration synergy to enable common IoT tasks.

(3) Compatibility: To achieve compatibility, the ontology must be consistent with those well-designed, existing ontologies.

(4) Modularity and scalability: To ease evolution, extension, and integration with external ontologies, the intended ontology was built using a highly modular approach.

3.2 – Ontology Components

DT/TI Applications (or Services), Service Test, QoS, Deployment System and Platform, Observation and Measurement, DT/TI Resources, and Entity of Interest are the seven primary modules in the description ontology, as proposed by [107] (Figure 3.1). Our proposed ontology, is inspired from the ontology of [107] and is depicted in Figure 3.2 as a whole. Only attributes are defined for some of the modules in the description ontology, so that we can link to concepts in external ontologies or existing linked data.

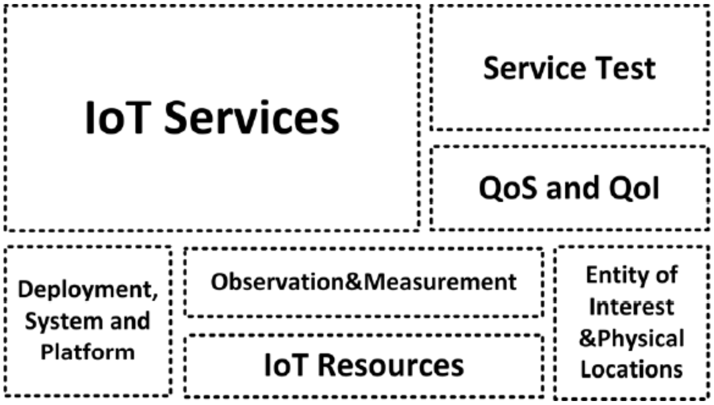


Figure 3.1: Components of the description ontology by [107]

(1) DT/TI resources: most existing DT/TI resource modeling work focuses on sensors and sensor networks [158, 159]. This module adds to the SODHO (an ontology for haptics - with sensors and actuators as main classes – that we developed previously throughout our research, and is explained in details in the coming paragraphs) by incorporating more DT/TI resources such DT/TI Gateway, and Server.

(2) DT/TI Applications (or services): The DT/TIs' scales and distributed natures necessitate scalable and interoperable methods for maintaining and accessing physical world data. Existing business applications and services that require intelligence and context awareness could be easily linked with low-level DT/TI services, thanks to the service interfaces exposed by DT/TI resources. Modeling DT/TI services in a way that adheres to existing service standards is a key concern (e.g., SOAP and REST based services).

(3) Quality of Service (QoS): QoS is a key concept in a variety of fields, mainly in networking, communication, and Web services. The DT/TI systems include a large number of delay-constrained and mobile resources with low or high compute capability that are typically used in dynamic environments. As a result, both DT/TI service providers and customers, QoS and QoE are very crucial in application (service) structure and adaption.

(4) Service Test: During the design and deployment stages, the test components are proposed for testing and verifying functional and non-functional capabilities of DT/TI services. They are linked to the ideas in the OWL-S process ontology, which aligns them with the services components.

(5) Deployment, Systems, and Platforms: This module describes how DT/TI resources are organized and deployed, as well as the systems that they create. By modeling and connecting these notions, a high-level perspective of the relationships between DT/TI resources and the networks, systems and platforms that support them may be obtained. Also here, we imported our previously developed ontology for 5G networks KPIs. The structure of this ontology is explained in details in the coming paragraphs.

(6) Observation and Measurement: the concepts in this module represent the data collected by DT/TI resources from the physical world. The SODHO and the SSN ontologies' concepts can be reused.

(7) Entity of Interest and Physical Locations: An entity of interest is a physical object that a user or program is interested in. Physical locations are related with entities of interest and are required for the identification of DT/TI resources and services.

3.3 – Our proposed Framework: Ontology Based Framework for Digital Twin and Tactile Internet - OFDTI

We recall that, in our work, modeling methodologies on Entity of Interest, and Observation and Measurement, are out of scope in this research. We expand on these activities, focusing on the modules that enable us to easily access, use, and verify data generated by DT/TI resources. We'll go over our modeling method for DT/TI Applications and Services, and QoS in the next paragraphs. Moreover, after talking at a glance about DT/TI Resources, and Network Deployment Platforms, we detail separately and respectively for each of the before mentioned modules, two ontologies that we developed previously (SODHO and KPION-5G), and that can be imported into our proposed new ontology. As for the Service (here application) Test module, it will include a

Fuzzy Information System (e.g. FIS, please refer to paragraph 3.6.2). To this module, we can import the results of three conducted applications test cases

that made the subject of Chapter 4. These applications test cases will validate the outcomes of the FIS of our proposed ontology platform.

As we can notice, we replaced: the “IoT Services” module of [107] by the “DT/TI Applications or Services”, the “QoS and QoI (Quality of Information)” by only “QoS” module, the “Deployment, System and Platform” by “Network Deployment and Platform”, and “IoT Resources” by “DT/TI Resources”, and we replaced in general, the “IoT” services by “DT/TI” services. We also, merged the two modules of “Service Test” and “Observation & Measurement” by one module, and we omitted the “Entity of Interest & Physical Locations” module. Finally, we can model our proposed OFDTI ontology as illustrated in the Figure 3.2 below:

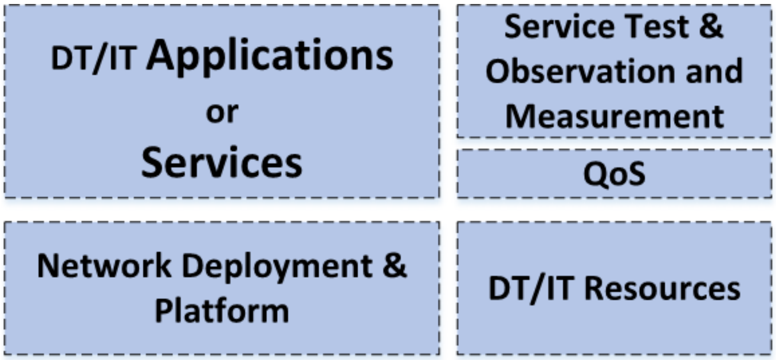


Figure 3.2: Components of the OFDTI ontology

3.3.1 – Network and Content Influencing Qualities

Tactile Internet is the future communication system that enables the communication of human sense of touch and actuation in a real time. The main technical requirements which define Tactile Internet are: extremely low latency, high availability, reliability and security [10]. Latency is considered the main challenge in making Tactile Internet available, and is defined as the time measured from the instant of sending haptic signal till receiving the response [5]. The network which could support haptic communications, must ensure all the requirements for a certain

Tactile Internet application. Different applications are offered by Tactile Internet, like teleoperation (depicted in figure 3.3), online gaming, remote surgery operations and mixed augmented reality. Because of the sensitivity and accuracy of these applications, the round trip time must be reduced as much as possible.

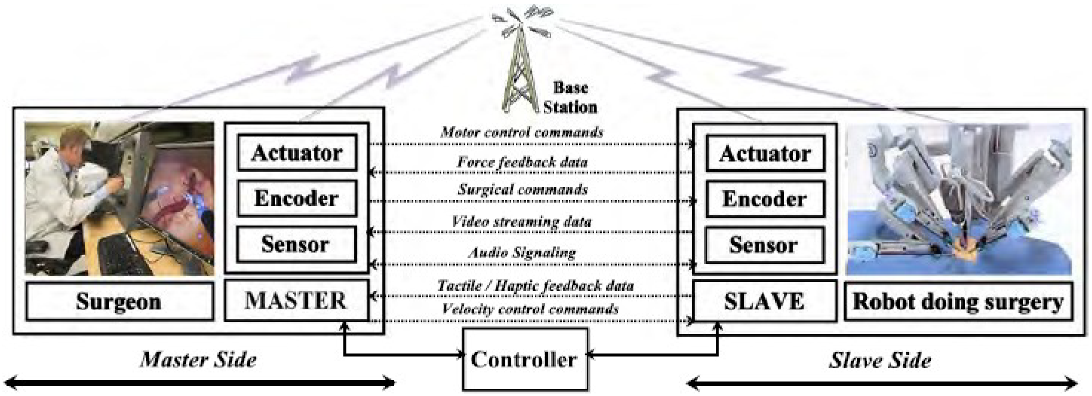


Figure 3.3: An Example of the Tactile Internet Application is Telesurgery system [62]

The functional architecture of Tactile Internet contains three main domains:

- The Master domain which is an operator with human system interface (HIS). (2) The slave domain, a teleoperator which is usually a controlled robot. (3) The Network domain which is the infrastructure connecting the aforementioned domains [3]. The network which could support haptic communications, must insure all the requirements for a certain Tactile Internet application. Different applications are offered by Tactile Internet, like online gaming, remote surgery operations, and augmented reality. Because of the sensitivity and accuracy of these applications, the round-trip time must be reduced as much as possible.
- The Network Quality of Service Key Performance Indicators are similar to the Network Influencing Quality. Key performance indicators are average measurements used by service providers to disguise the real experience of users and are specific to a particular technology. Clearly, generic QoS issues (e.g., packet loss, latency, delay variation, reordering, and bandwidth shortage) imply generic QoE issues (e.g., jittering, artifacts,

instability, glitches, and long wait times). As a result, in this lingo, QoS-KPIs relate to the network provider's quantitative and/or qualitative performance elements of media transmission across the network. This part looks at the qualities of a telecommunications service that affect its ability to meet the stated and implicit needs of its users (Figure 3.4).

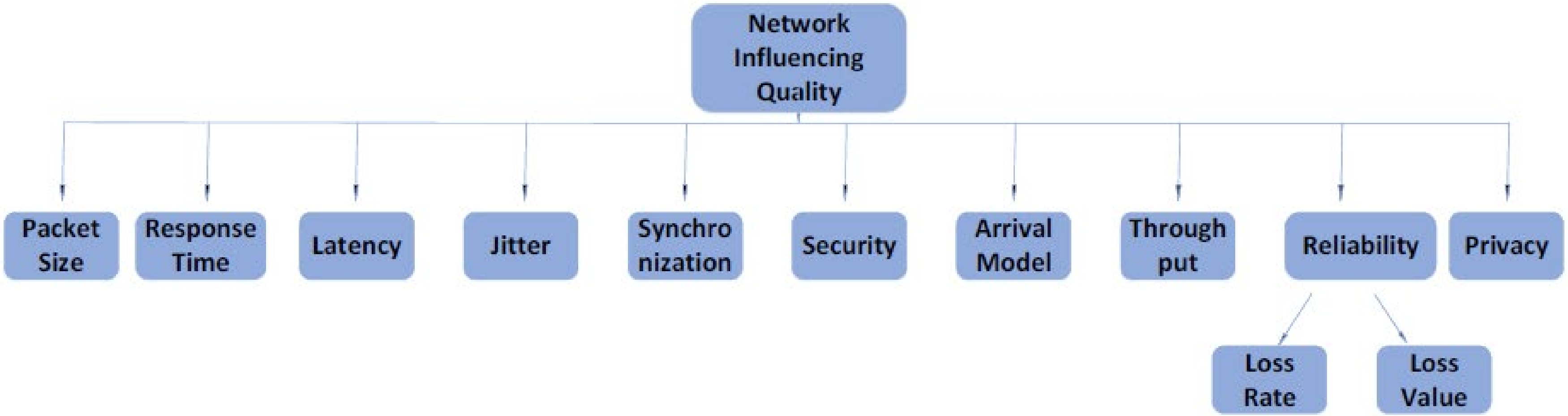


Figure 3.4: Network Influencing Quality (refined from [148, 183])

The majority of the KPIs utilized to ensure the quality of service for the new advanced DT/TI networked application are highlighted below. For that, we recall the teleoperation system, which, without a doubt, is a rapidly expanding discipline of DT/TI that combines robotics, telecommunications, and data processing. The capabilities of the networks are clearly established by the requirements of the use cases that will need to make efficient use of the network. We must repeat through the use cases in order to extract the requirements. This is something that the 3GPP has already done, mostly in [138], with further details in [139]. Table

3.1 lists the use cases (or applications) using the first classification described in [138], as well as a few examples and a summary of the important KPIs and conditions that must be met for users to have a good QoS.

Teleoperation is mostly related to the first three use case categories, but because there is such a wide range of applications, the various requirements can be classified into many different types. The names of the use case families, as shown in Table 3.1, are self-explanatory, as they comprise some or all of the main KPIs indicated. These KPIs were chosen to highlight the fundamental similarities and differences between the use cases.

These are some of them:

- **End-to-end latency (e2e latency)**: The total of a packet's transmitting delay, propagation delay, and waiting time is the End-to-End latency. This can also be expressed as = processing time + queuing time + transmission time + propagation time. We can find: (1) Audio Latency, (2) Video Latency, and (3) Network Latency.

- **Throughput**: The amount of bandwidth that the multimedia channel has available. The amount of data sent from the sender to the receiver is also known as the data transmission rate, or simply, **data rate**. Bits/second, bytes/second or even packets/second, are the most common units of measurement.

- **Update rate:** How often does each modality's data need to be refreshed per second. It is not to be confused with the sampling rate, which is measured in Hz.

- **Reliability**: The total number of packets transmitted divided by the number of packets successfully received by one end node (percentage).

- **Availability**: The time the communication system can give service to the user divided by the total period the services are expected to be delivered.

- **Mobility:** The rate at which a user requests services from a network providers. Telesurgery with the patient inside a fast-moving ambulance is one example.

- **Arrival model**: The arrival and loss characteristics of the Internet's modality packet are defined by this property. It can take the form of a periodic, aperiodic, Markov, or Bernoulli system.

- **Coverage** refers to the geographic area in which a network provider can provide services.

- **Positioning precision**: The degree to which a user's location can be tracked with accuracy.

- In many circumstances, maintaining the **integrity** of the data is a basic need. We also discuss the related concept of **confidentiality** in Table 3.1, which relies on the network operator's choice.

- **Service continuity**: Even when a service is offered to a user in a different fashion, it must be done in a seamless manner. This shift could be in the form of a new access technique (e.g. satellite).

Classification of use cases	Examples of traffic schemes	Principal KPIs	Specifications
Greater dependability, availability & lower latency	• Ambulance medical treatment • Industrial applications with low-latency • Telemedicine cloud applications	e2e latency Reliability Availability Mobility Data rate	≤ 1 ms ≥ 99,999% ≈ 100% ≥ 120 km/h tens of Mbps per device
Very low latency	• Tele mentoring, Remote healthcare, Human interaction, Immersive VR	e2e latency	1 ms one-way
Mission crucial services	• Prioritized access when: the network is congested, simpler access procedures or guaranteed QoS are needed	e2e latency Reliability Security	down to 1 ms ≈ 100% max. confidentiality & integrity
Greater reliability & lower latency	•Unmanned Aerial Vehicles (UAVs) & Ground-based Vehicles • VR/AR applications • Cloud robotics • Industrial applications/ Power plants	e2e latency Reliability Data rate Energy efficiency	1 ms min. 99,999% 250 Mb/s max. Various or NA
Higher accuracy positioning	• Outdoor positioning (high speed moving) • Indoor/Outdoor positioning (low speed moving) • UAV positioning for critical applications	Accuracy e2e latency Mobility	≤ 3 m for 80% of occasions ≤10 ms to 15 ms two-way ≈ 280 km/h (cars)
Greater availability	• Secondary connectivity for emergencies (mobile-to-satellite)	Coverage	Service continuity

Table 3.1: Examples of 5G use cases with their matching specifications for the principal KPIs

Besides the networking influencing quality metrics, cited before, we also stress on the content influencing quality metrics, which is the heart of any multimedia system. It deals with the DT/TI modality's codecs as generated by the content provider. In this context, the most effective and extensively used codecs for video, audio, kinesthetic, and tactile information exchange via communication networks are High Efficiency Video Coding (HEVC), also known as H.265, Dolby vision/Atoms, and IEEE P1918.1.1. In the MR (Mixed Reality) modality, both VR (Virtual Reality) and AR (Augmented Reality) are considered independently first, then blended and followed by mixed modalities.

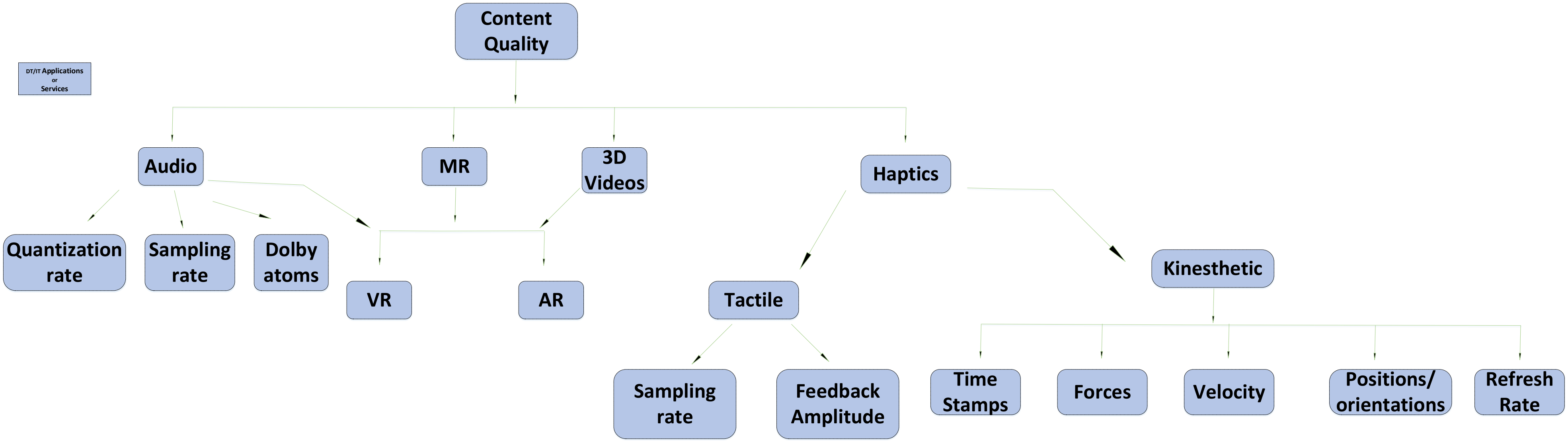


Figure 3.5: Content Influencing Quality (refined from [148,183])

3.3.2 – Taxonomy for Tactile Digital Twin/Tactile Internet

Now that we went through the network and content qualities, we can classify the aforementioned KPIs, into 2 categories: The Networking KPIs, and the Applications KPIs. This classification is useful for the ontology to infer, as stated before in the abstract, the most adequate network type for a certain DT/TI application. That means, feeding the ontology with the two abovementioned categories, along with a given application, a reasoner (as in the previous SODHO ontology) can correlate between these KPIs to figure out the result. The second category (i.e. networking KPIs) is summarized in the Table 3.2 below, for 5 types of mobile communications systems: Wi-Fi, WiMAX, 3G, 4G, LTE-A, and 5G, along with the most important networks KPIs and their standard values: E2E delay, Jitter, Throughput, and Data rate. In all our work, we have prioritized the first three metrics, because they give relevant scheme for the delay-sensitive applications in general.

	Round-trip Latency or E2E delay (ms)	Jitter (ms)	Throughput (Xbps)	Data rate: downlink/uplink (Xbps)
Wi-Fi	2 < E2E delay < 20	< 30	Up to 600 Mbps	From 25 Mbps
WiMAX	< 25	< 50	70 Mbps	25/6.7 Mbps
3G	≅ 100-500	0 to > 10	3.1 Mbps	7.2/2 Mbps
4G	<20	0 - 6	100-300 Mbps	128/56 Mbps
4.5G/LTE-A	<20	0 - 1	1 Gbps	3/1.5 Gbps
5G	<1	< 0.01	10 Gbps	20/10 Gbps

Table 3.2: 5 types of mobile networks KPIs

Through all the services and the applications of Tactile Internet and Digital Twin cited before in this thesis, we chose a set of DT/TI applications - that we find the most relevant, and proposed a taxonomy of DT/TI for ultra-reliable low latency applications, as follows in Figure 3.6. The taxonomy is built on a hierarchical basis, with quality influencing and assessment aspects, all taken into account.

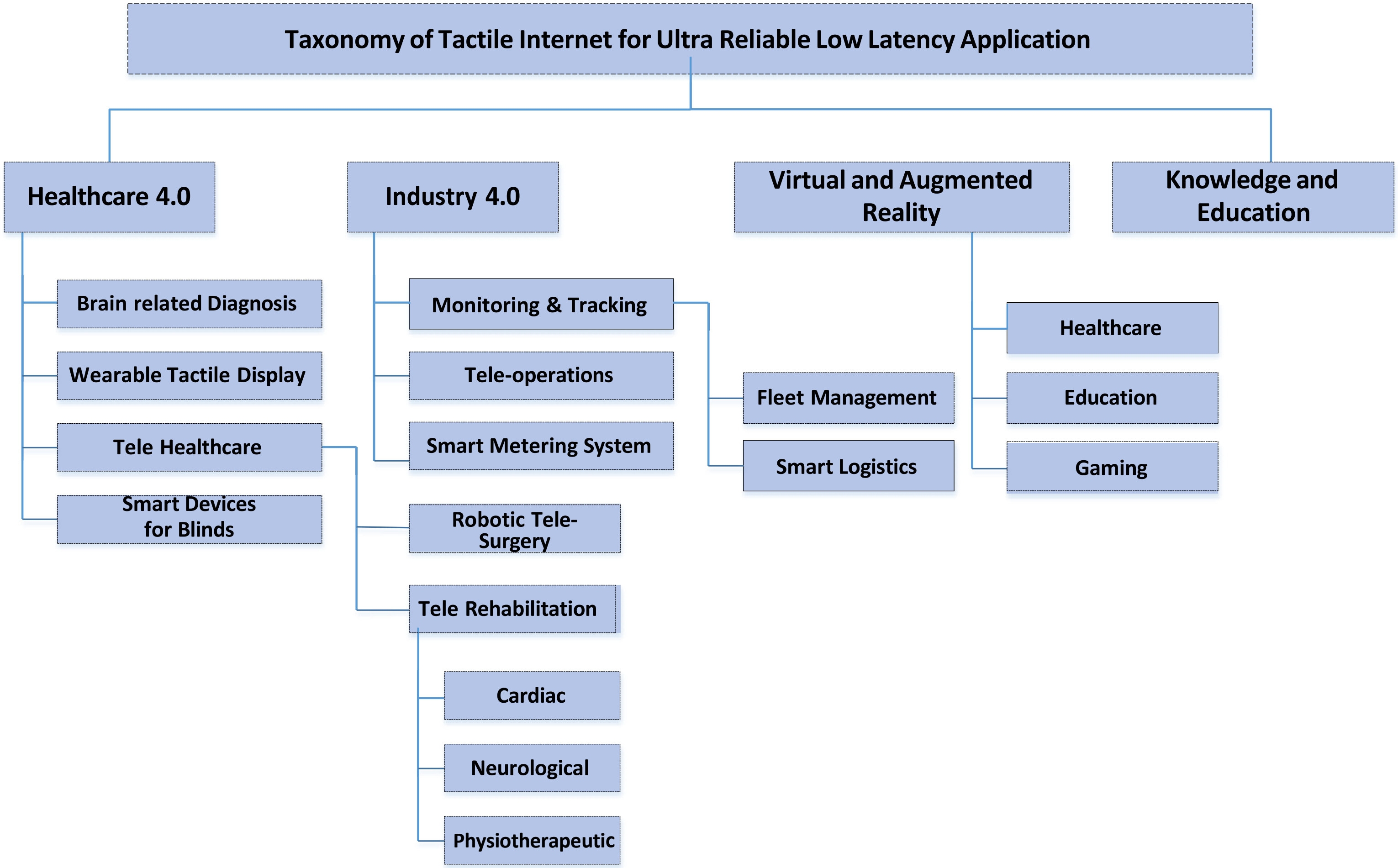
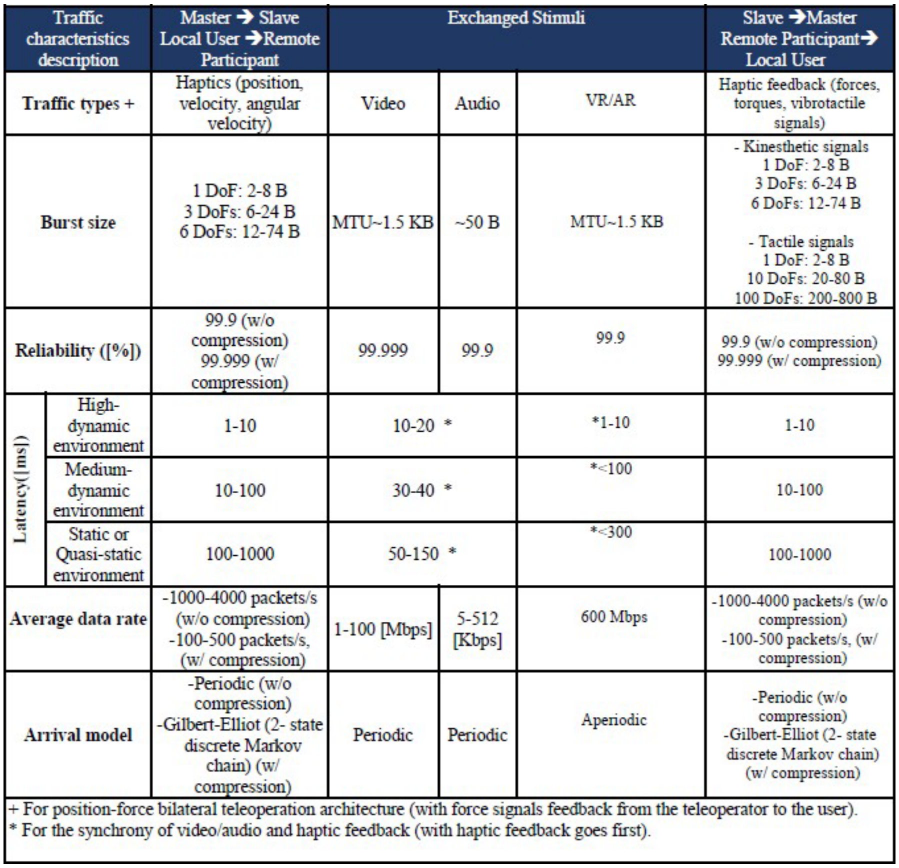


Figure 3.6: TI deployment taxonomy for ultra-reliable low-latency haptic applications (High level)

To assess the performance of our framework, we recall the Tele-operation application of Figure 2.3 of Chapter 2 (Background and related works). We present, in Table 3.3, the KPI requirements for the DT Tele-operation application modalities over Tactile Internet.



Traffic characteristics description		Master → Slave Local User → Remote Participant	Exchanged Stimuli			Slave → Master Remote Participant → Local User
Traffic types +		Haptics (position, velocity, angular velocity)	Video	Audio	VR/AR	Haptic feedback (forces, torques, vibrotactile signals)
Burst size		1 DoF: 2-8 B 3 DoFs: 6-24 B 6 DoFs: 12-74 B	MTU~1.5 KB	~50 B	MTU~1.5 KB	- Kinesthetic signals 1 DoF: 2-8 B 3 DoFs: 6-24 B 6 DoFs: 12-74 B - Tactile signals 1 DoF: 2-8 B 10 DoFs: 20-80 B 100 DoFs: 200-800 B
Reliability ([%])		99.9 (w/o compression) 99.999 (w/ compression)	99.999	99.9	99.9	99.9 (w/o compression) 99.999 (w/ compression)
Latency([ms])	High-dynamic environment	1-10	10-20 *		*1-10	1-10
	Medium-dynamic environment	10-100	30-40 *		*<100	10-100
	Static or Quasi-static environment	100-1000	50-150 *		*<300	100-1000
Average data rate		-1000-4000 packets/s (w/o compression) -100-500 packets/s, (w/ compression)	1-100 [Mbps]	5-512 [Kbps]	600 Mbps	-1000-4000 packets/s (w/o compression) -100-500 packets/s, (w/ compression)
Arrival model		-Periodic (w/o compression) -Gilbert-Elliot (2- state discrete Markov chain) (w/ compression)	Periodic	Periodic	Aperiodic	-Periodic (w/o compression) -Gilbert-Elliot (2- state discrete Markov chain) (w/ compression)

+ For position-force bilateral teleoperation architecture (with force signals feedback from the teleoperator to the user).
* For the synchrony of video/audio and haptic feedback (with haptic feedback goes first).

Table 3.3: KPI Requirements and Traffic Attributes for DT Teleoperation over TI (refined from [183])

3.3.3 - -Simulating DT/TI Applications

DT/TI resources expose DT/TI services, which typically give (near) real-time and transient information on the physical environment via standard service interfaces. They typically operate in dynamic situations where resources (such as processing, and communication capabilities) are limited and may emerge at any time.

3.3.3.1 - DT/TI Applications (or Services)

Because of the nature of DT/TI resources and their operating settings, DT/TI applications are less reliable than well-engineered high-level business services. This demands extra mechanisms adaption throughout the service (here the application) lifecycle (e.g., QoS of DT/TI services). We define a DT/TI Service as a subclass of the OWL-S Service class [156], so it can have one Service Profile and one Process that characterize its functional and non- functional attributes (they are inherited from the OWL-S Service class). As illustrated in Figure 3.7.a, a connection "exposes" (and its inverse property "isExposedBy") is created between a DT/TI Resource and a DT/TI Service.

The "hasQoS" relation relates the DT/TI Service class to the QoS concept, which is described as a separate class.

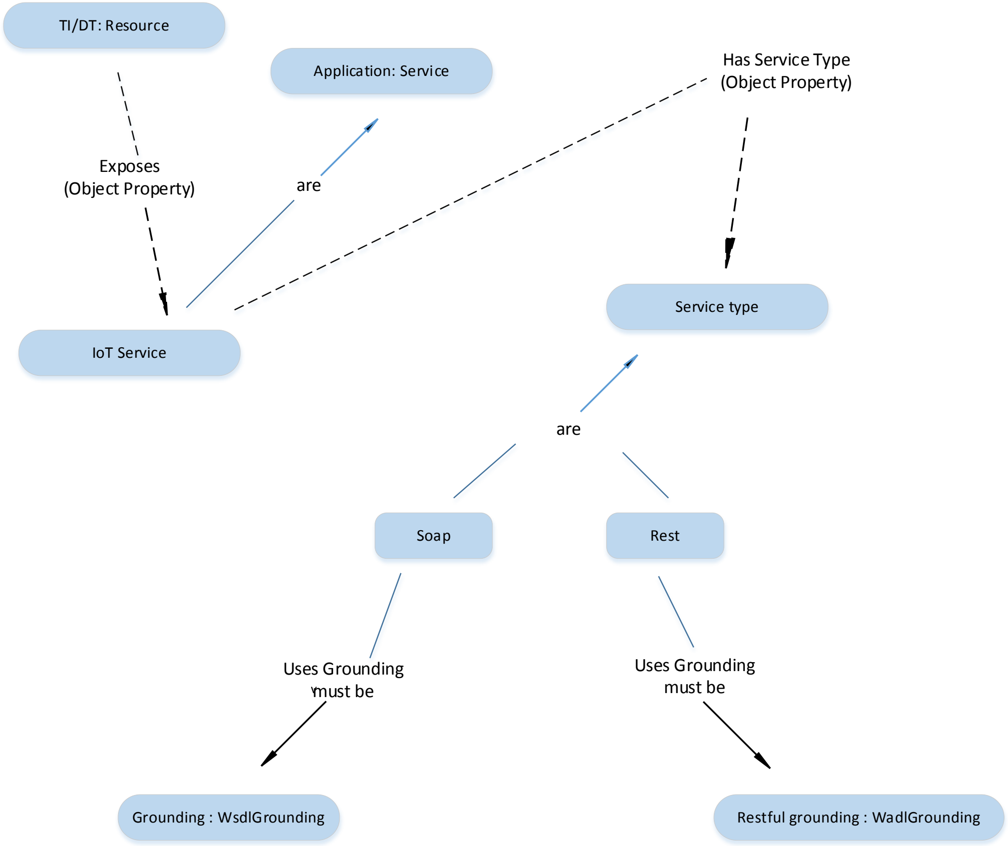
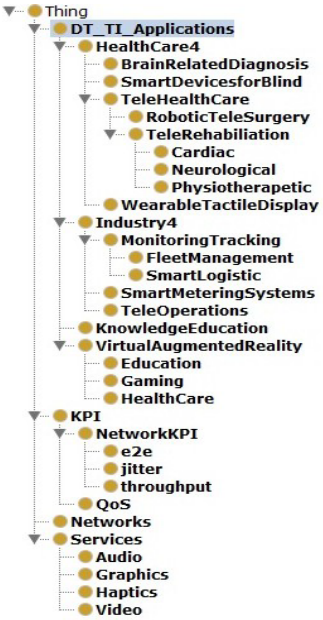


Figure 3.7: (a) The description ontology's DT/TI services and resources



- Thing
  - DT_TI_Applications
    - HealthCare4
      - BrainRelatedDiagnosis
      - SmartDevicesforBlind
      - TeleHealthCare
        - RoboticTeleSurgery
        - TeleRehabiliation
          - Cardiac
          - Neurological
          - Physiotherapetic
      - WearableTactileDisplay
    - Industry4
      - MonitoringTracking
        - FleetManagement
        - SmartLogistic
      - SmartMeteringSystems
      - TeleOperations
    - KnowledgeEducation
    - VirtualAugmentedReality
      - Education
      - Gaming
      - HealthCare
  - KPI
    - NetworkKPI
      - e2e
      - jitter
      - throughput
    - QoS
  - Networks
  - Services
    - Audio
    - Graphics
    - Haptics
    - Video

Figure 3.7: (b) The three main classes: DT_TI_Applications, KPI, and Services in OFDTI

In this ontology, as shown in the snapshot of Protégé in Figure 3.7.b, we can see the three classes: “DT_TI_Applications”, “KPI”, and “Services”. From “Thing”, which is superclass of everything, then consequently from the three before mentioned classes, the other sub-classes, each within the general taxonomy of Figure 3.6, and the two taxonomies of Figures 3.4 and 3.5.

From there, we can create subclasses of any class, for example: “DT_TI_Applications” is class, and “HealthCare” is subclass of “VirtualAugmentedReality”. Both are subclasses of “DT_TI_Applications”.

We expect that DT/TI services will be developed using SOAP (Simple Object Access Protocol) or REST-based (REpresentational State Transfer) techniques, and we choose OWL-S as the primary language for describing DT/TI services in our architecture. The OWL-S [156] ontologies Profile, Process, and Service are used to define the functionality and processes of IoT services. This retains the service attribute of being process-oriented, i.e., RESTful services can participate in service composition with SOAP-based services, and provides design consistency by using a single language for defining different types of services technology.

3.3.3.2 - Quality of Service (QoS) Key Performance Indicators

(KPIs)

QoS and its KPIs have been investigated extensively in a variety of fields, including networking and communication, Web services [163], and can be utilized as important criterion for constructing complicated service composition and adaption algorithms [164]. They are especially critical in the DT/TI area, which has a considerably higher level of dynamicity. We do not attempt to enumerate and model all of the factors for QoS in our work because they are frequently application dependent. Rather, we establish parameters that are common to a wide range of application domains. Both KPI and QoS are modeled as classes (with QoS subclass of KPI, and a number of other subclasses for each) and related to both the DT/TI Applications class and the DT/TI Resource class in the current version of the ontology, as shown in Figure 3.8., KPI is the top-level QoS KPI class with networking-related subclasses (e.g., Throughput and Delay), Availability, Reliability, Security, and so on. The properties "CalculationValue" (the value of the QoS parameter) and "CalculationMethod" are shared by all of these classes (method for calculating the QoS value). A computation technique that can be described using appropriate expressions or URIs to simplify the reuse of QoS falls within the scope of the "CalculationMethod" property. A Min and Max Value or a Value List with an optional Exact Value constrain the values of service attributes. Figures 3.9.a and 3.9.b depict portions of the description

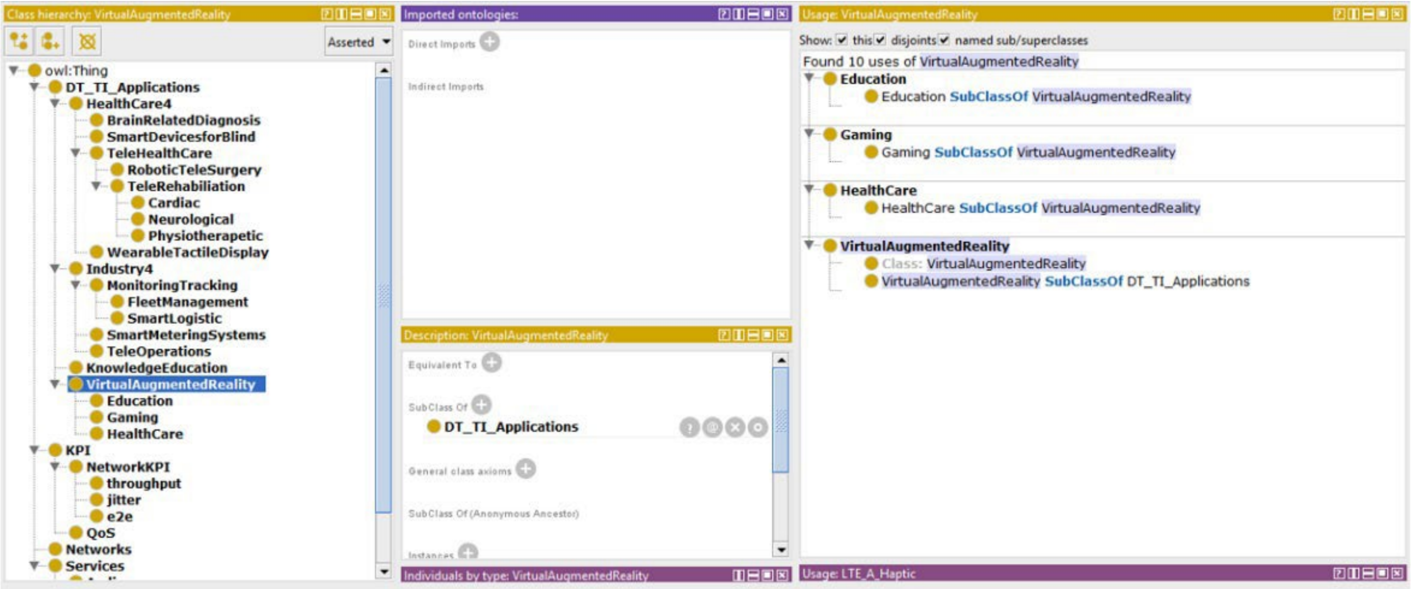
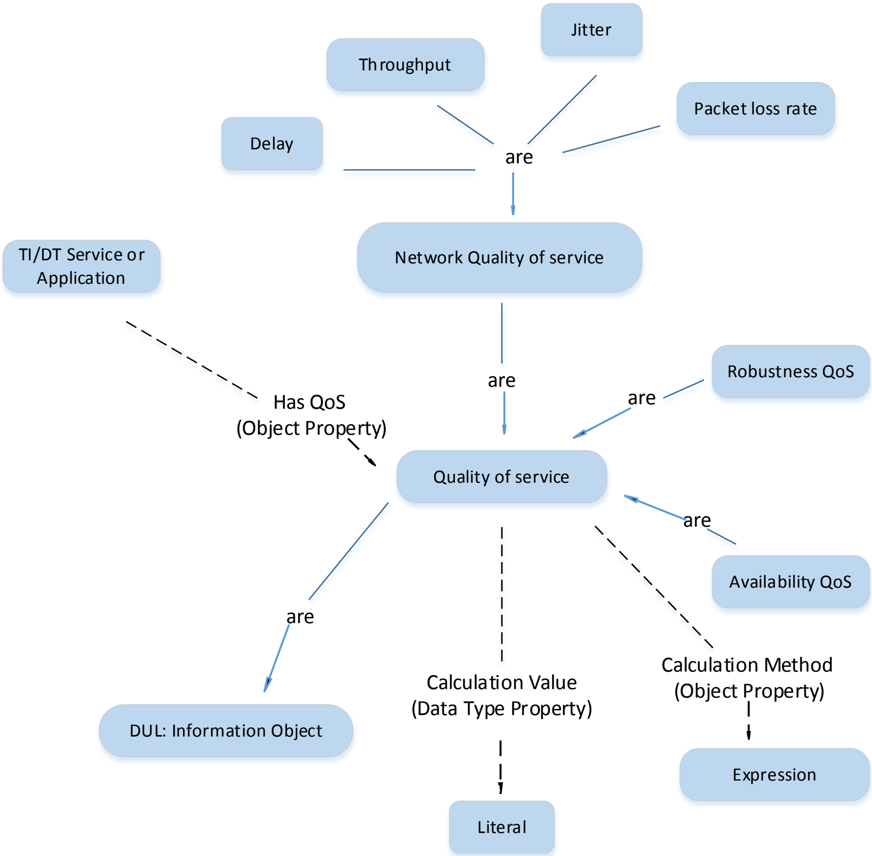
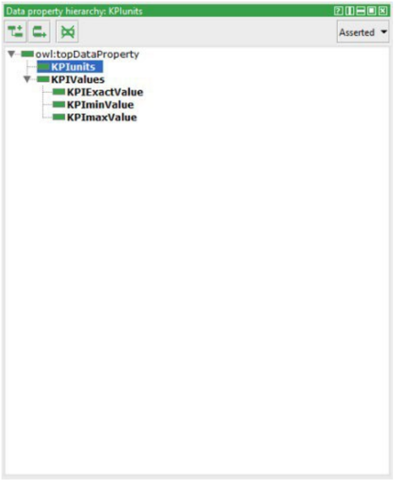


Figure 3.8: KPI Class and its subclasses in Protégé

OFDTI ontology.



(a)



(b)

Figure 3.9: (a) KPI in OFDTI ontology, (b) KPI Data property in Protégé

3.3.3.3 - Service Test

The distributed and heterogeneous nature of DT/TI applications and services necessitates strong testing capabilities: For instance, to guarantee that the performance of the services matches the needs of users and service level agreements between service providers and consumers. The test technique is linked to service process modeling, and the above- mentioned service models are used to specify test cases, test data, and test flow. This ontology will leverage (in the future) OWL-S [156] principles to specify service test semantics, such as inputs, outputs, preconditions, and named effects (IOPE).

3.3.3.4 - Tactile Internet/Digital Twin Resources

As stated before in the paragraph 3.2 "Ontology components", that most existing DT/TI resource modeling work focuses on sensors and sensor networks [158, 159]. This module adds to our SODHO (an ontology for haptics - with sensors and actuators as main classes) by incorporating more DT/TI resources such DT/TI Gateway and server. In the following paragraph 3.4, we focus only on the transducers (sensors and actuators) part in SODHO, and we let the gateway and the server for future work in SODHO, and then import the updated latter into our proposed OFDTI ontology.

3.3.3.5 - Network Deployment, Systems, and Platforms

Again, as stated previously in paragraph 3.2 "Ontology components", this module describes how DT/TI resources are organized and deployed, as well as the systems that they create. By modeling and connecting these notions, a high-level perspective of the relationships between DT/TI resources and the networks, systems and platforms that support them may be obtained. Also here, we imported our previously developed ontology for 5G networks KPIs. The structure of this ontology is explained in details in paragraph 3.5.

3.4 - SODHO: Service Oriented Development of Haptics Ontology

In [112], multimedia haptics is defined as the following:

"The collection of spatial, temporal, and physical understanding of the environment via the human touch sense organs, as well as the integration/coordination of this understanding with other sensory modalities (such as audio, video, and text) in a multimedia system”.

The roadmap toward multimedia haptics, has three different paths: human haptics, machine haptics, and computer haptics. Today, any human-haptic machine interaction system design is based on the three subsystems: human haptics subsystem, machine haptics subsystem and computer haptics subsystem.

In this thesis, our major concern, is the first two subsystems:

The study of human perception and manipulation through tactile and kinesthetic feelings is known as human haptics. The interaction force or pressure is imposed on the skin when a person touches an object. The brain receives this information from the related sensory system, which translates to awareness. As a result, the brain sends out motor commands to the muscles, causing hand and arm movements.

Designing, engineering, and developing mechanical equipments that mimic or amplify human touch is known as machine haptics. These devices, also known as haptic interfaces, are placed in physical touch with the human body in order to exchange (measure and display) data with the human nervous system. Essentially, haptic interfaces serve two purposes: first, they quantify the poses (positions and/or orientations) and/or interaction forces of any area of the body, and second, they exhibit the computed reaction touch to a haptic display that contains touchable virtual objects with haptic attributes such as friction, stiffness, and harshness.

Sensors (receptors-nerves in the human subsystem and sensors in the machine subsystem) are present in both subsystems, as are processors (brain in the human and computer in the machine subsystem) and actuators (muscles in the human and actuators in the machine subsystem).

In the following, we present an ontology by integrating and extending existing work in modeling concepts on haptics to give a unified ontology for sensors and actuators (or in general transducers). The work presented hereafter, is inspired from a previous ontology the “HASM” [111]. The objective of this work aims at giving a unified model and a lightweight ontology, that serves for the building of a Multimedia Haptics ontology and thus, users and applications can benefit from a formal taxonomy of the haptics domain, in a service-oriented vision, especially for tactile and kinesthetic interfaces and the design of haptics audio visual environments, all this within the DT/TI arena. For the sake of a unified and integrated model of Haptics Ontology, and to target a future Multimedia Haptics ontology, we present SODHO, the Service Oriented Development of Haptics Ontology based on Web Ontology Language OWL and specifically Protégé. We go through the road that facilitates the understanding of the Ontology classes, subclasses, object properties and the relationship between them, while describing the most relevant characteristics of the components (sensors and actuators) that build a Haptic Interface System HIS.

3.4.1 - SODHO Principles

To better develop a proper haptic rendering algorithm, we need to know the physical, spatial and temporal attributes of haptic devices, which lies in machine haptics [6]. Therefore, it is needed to acquire knowledge about the existing sensory and actuation hardware technologies and the control of such devices in the machine subsystem.

In the context of our thesis, we consider the SUMO (Suggested Upper Merged Ontology) reference ontology, as in [110], because it comprises low-level details ontologies for various domains, where the computing services domain (networks, systems, devices, and services) plays a crucial role. The main goal of this work is to gather information about physical entities (the sensors and actuators) and their corresponding relationships. The roadmap towards accomplishing this goal begins with HASM and continues by defining and classifying the attributes of haptic devices of the machine subsystem into: physical, spatial and temporal attributes. These attributes constitute a family of new classes (attributes classes), comparing to HASM (in which objects and processes classes are the main components). This will lead to design an ontology for sensors and actuators specific for multimedia haptics applications, and moreover for the IOT, such as smart environments, real/virtual environments, augmented reality, tangible user interfaces, etc.

The motivation behind choosing the SUMO model is that, with its domain ontologies, they constitute one of the biggest explicit public ontology in presence today. They are mainly being used for research and applications in graph theory, search, reasoning, and reasoning testing. SUMO is lengthened with many domain ontologies and is freely available [114]. Moreover, its modularity (divided into SUMO itself, MILO - MId-Level Ontology, and domain ontologies) and its dimension (richness in terms and axioms - 20,000 terms and 60,000 axioms including domain ontologies), make it on the top of our choice decision making.

With the help of the light use of SUMO in OWL (Protégé version), we think we started the building of a fully integrated model of Haptics Ontology, and at the beginning, we focused only on the machine subsystem of the haptic interface, thing to be complemented by the human subsystem in a future work in order to model all subsystems and derive their relationships.

In the following sections, we will present the most relevant attributes for an HIS used in our ontology, then derive a topology of this ontology represented by an Ontograph. We then check the consistency of this topology using the FaCT++ "Reasoner" implemented in the OWL–Protégé 4.3.0.

3.4.1.1 - Performance specifications of a Haptic Interface System

In SODHO, we classify the attributes of a HIS into three categories [112]: Physical attributes, spatial attributes and temporal attributes. Below (for each actuators and sensors), is a non-exhaustive list of the most important attributes.

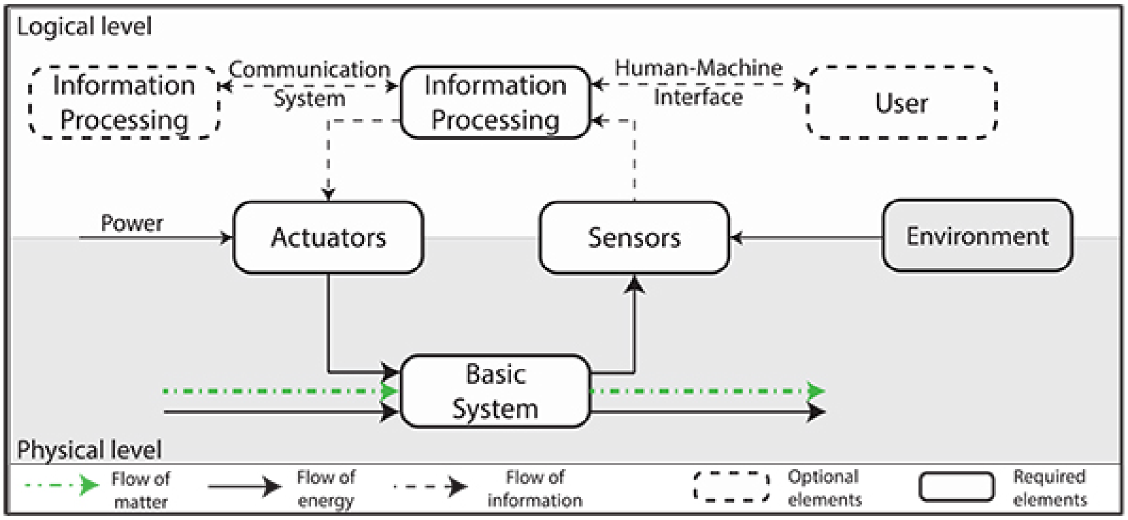


Figure 3.10: Haptic Interface System [118]

A - Actuators

Physical attributes

Inertia: This attribute depends on the mass of the haptic device.

Backdrivability: The ability to move the end-effector of the device.

Friction/Damping: comes in two forms: Coulomb friction, and viscous or damping friction position/resistance.

Exertable Force Attributes: Characterize the ability and flexibility of the device to generate force feedback (such as maximum exertable force, continuous force, and minimum displayed force).

Stiffness: The ability of a device to mimic a solid virtual object.

Size/Weight: The size and weight of a haptic interface has a direct impact on the comfort level of the user.

Spatial attributes

Workspace: The area or volume in real world space that the end-effector of a haptic device can reach.

Position Resolution: Defined as the smallest amount of movement over which the position sensors can detect a change in the position of the end-effector.

Degree of Freedom: Number of independent directions along which the haptic interface is able to display motion, sensing, or actuation capabilities.

Precision and Repeatability: Precision refers to how accurately the position sensor can refer to its position. Repeatability represents how accurately the haptic device can sense the identical physical position as being the same virtual position.

Grounding Location: The grounding location is the base reference that the device is attached to.

Temporal attributes

Device Latency: Is the time measured from the instant of sending a command to the device to the instant of receiving a response.

Bandwidth: Is defined as the range of frequencies over which the hand-controller provides force feedback.

Haptic Refresh Rate: Is the speed at which the feedback loop can be completed, and it is usually expressed in Hertz. Maximum Acceleration: Reflects the ability of a haptic device to simulate stiffness of virtual objects like walls.

Haptics Update Rate/System Latency: Includes sensing the position of the haptic device, computing the force feedback in the simulation, sending the force to the device, and reading the next position.

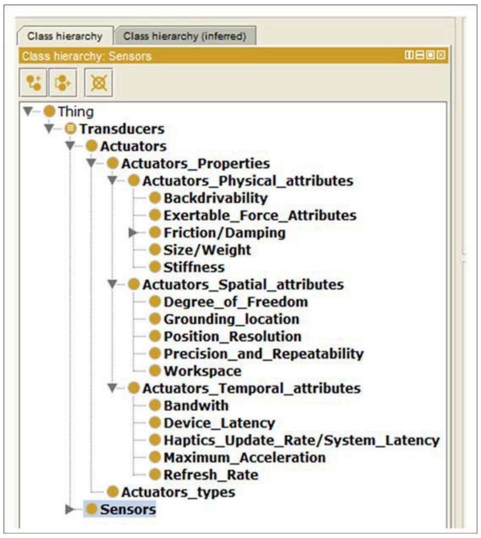


Figure 3.11: Actuators attributes within SODHO model in Protégé

B - Sensors

Physical attributes

Voltage required: The range of voltages across which the sensor produces a steady output. A voltage that is too low will cause the sensor to malfunction, while a voltage that is too high will cause something to burn out.

Sensor Noise Estimation: Aside from digitizing noise, there is another measuring constraint owing to the intrinsic noise in a sensor. Because we now have the technology to reduce the digitizing interval or digitizing noise to levels below sensor noise, the limiting element in a measurement is usually the sensor's physics.

Range: Is the range of values between which a sensor performs properly. Sensors frequently perform well outside of this range, although special or additional calibration is required.

Output: a voltage range, such as 0 to 5 volts for an input temperature range of 0 to 30 degrees Celsius, or a frequency modulated sine wave, or a square wave with a frequency range of 6 to 12 kHz, etc.

Cable Diameter: The wire gauge, or wire diameter, influences how much weight it may safely transport. Wire diameters are measured by code inspectors to ensure that they are safe to use in systems.

Cable Wires: A wire is used to convey electricity, support mechanical loads, transmit communications signals, and to build automotive or industrial parts. Telecommunication signals, power transmission, and electricity are all carried through cables.

Sensor Plate Thickness: The distance between the two sensor's surfaces under a certain applied pressure, which fluctuates if the plate is compressible

Surface Utilization Ratio: The occupancy of a surface divided by its capacity is the basic definition of surface usage ratio. This tells you a proportion of how much of a sensor's surface is used against how much isn't.

Sensor Size: Relates to the sensor's physical dimensions and is rarely included on specification sheets. The best technique to figure the sensor size is to multiply the resolution by the pixel size of the sensor.

Spatial attributes

Accuracy: In a strict way, how well the sensor detects the environment. When compared to a known standard, this indicates how good the data is.

Dynamic Calibrations or Frequency Response: A sensor is a filter that changes the frequency content of the data it receives. It is the experimenter's responsibility to ensure that these filtering effects are understood and do not interfere with the desired results.

Repeatability: When a sensor is placed in the same environment, it has the capacity to repeat a measurement. It's commonly linked to precision, yet a sensor might be imprecise while still being repeatable in its observations.

Resolution: A sensor's ability to detect minor variations in measurements.

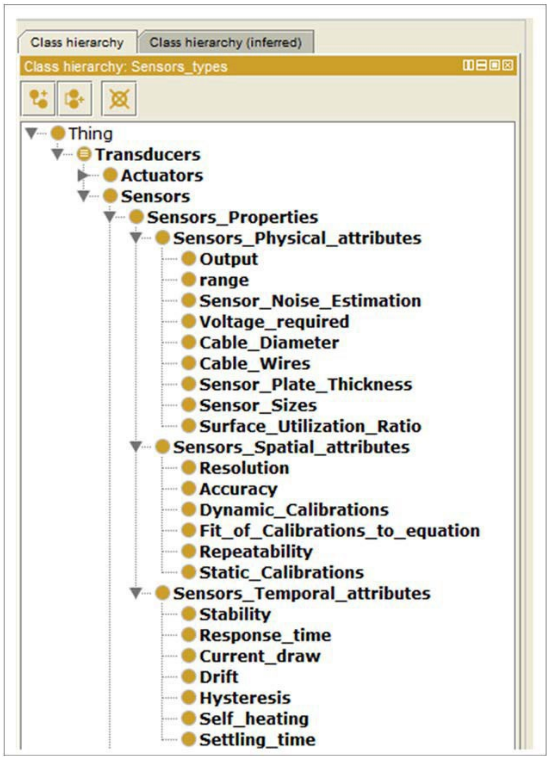


Figure 3.12: Sensors attributes within SODHO model in Protégé

Temporal attributes

Response time: A basic estimation of a sensor's frequency response based on exponential behavior.

Settling time: When the sensor is turned on, the time it takes for it to reach a stable output. As a result, if you're saving power by shutting off the sensors between measurements, you'll need to turn them back on and wait a specific amount of time for the sensor to stabilize.

Drift: This is the time-dependent low frequency change in a sensor. It's frequently linked to the sensor's electronic components or reference standards aging. As the component parts of a sensor develop, the amount of drift reduces.

Stability: Is another way of expressing the concept of drift. That is, you always receive the same result from a given input. Drift, short-term stability, and long-term stability are all ways of representing noise as a function of frequency for a sensor. This is sometimes presented as a guarantee of accuracy for a specific time period. Under high pressure, pressure sensors are prone to drift. With the passage of time, all sensors wander.

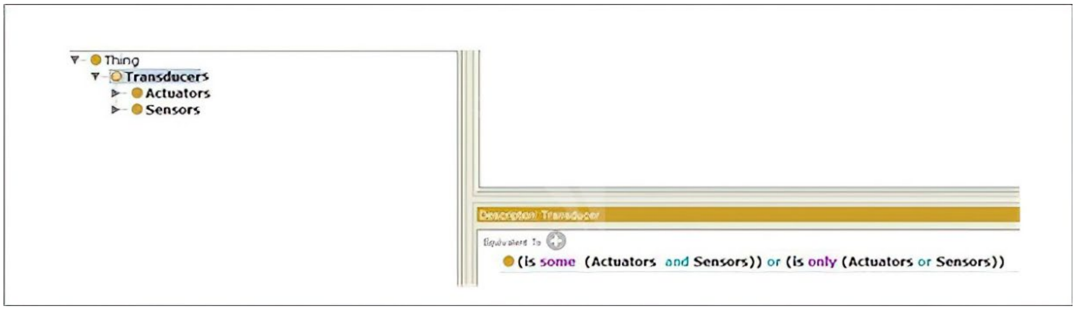
3.4.1.2 - Structure of SODHO: Ontograph

Ontologies are used to create information models that allow users to explore the information space in terms of the items represented, their affiliations, their properties, and the links to documentation that describes and defines them. Names for essential domain concepts and background knowledge/constraints are often found in ontologies.

The elements of an ontology are:

- Concepts (classes) + their hierarchy
- Concept properties (slots/attributes)
- Property restrictions (type, cardinality, domain)
- Relations between concepts (disjoint, equality)
- Instances

In our ontology, as shown in the snapshot in Figure 3.13, we can see the two classes: “Actuators” and “Sensors”. From “Thing”, which is superclass of everything, then consequently from “Transducers”, the two classes “Actuators” and “Sensors” are created and are inspired from their close relationship to the superclass “Transducers”.



(is some (Actuators and Sensors)) or (is only (Actuators or Sensors))

Figure 3.13: “Transducers” and its subclasses in SODHO

From there, we can create subclasses of any class, for example: “Sensors_Physical_attributes” is class, and “Sensor_Sizes” is subclass of “Sensors_Physical_attributes”. Both are subclasses of “Sensors”.

We can add/delete and edit properties and make some relation between classes and others. We can find in [115] more information on object properties and the SWRL (Semantic Web Rule Language) that governs the generation of rules for a given ontology.

The relation is very important between the classes. We should specify the relation for each class by restricted property - which we built - and the restriction type (some, only, min, max

…) with restriction filer [115].

Finally, the Ontograph (Figure 3.14) visualizes the binding of some of the classes and subclasses and shows the relationships between them in a graphical mode, hence it facilitates the common understanding of Ontology.

We can have different views of the Ontograph: horizontal or vertical designs.

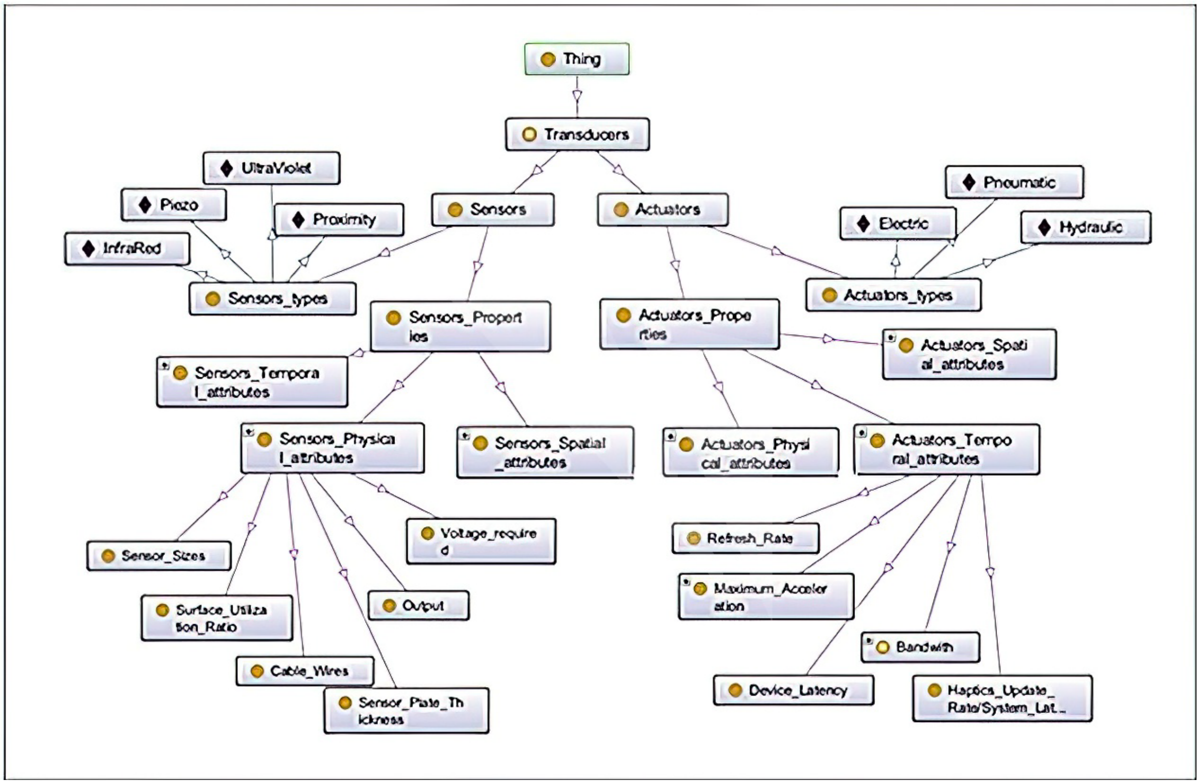


Figure 3.14: SODHO Ontograph in Protégé

3.4.1.3 - SODHO consistency checking with FaCT++ Reasoner

When creating SODHO, we intend to check the logical consistency of the model behind it.

This is one of the tasks, among other, that can be done by the “Reasoner”.

The reasoner is the main component in querying the ontology. It is a piece of software able to infer information that is not explicitly contained within the ontology. It is also referred as Classifier.

The main features of a reasoner are:

- ✓ Consistency checking, that ensures that our ontology doesn’t contain any conflicting facts.

- ✓ Identifying subsumption relationships between classes.
- ✓ Ontology analysis and repair.
- ✓ Serving for equivalence and instantiation checking.
- ✓ Satisfiability that verifies for each class if it is possible to have instances.

In our model, we used the FaCT++ reasoner [116]. The driving forces behind the use of FaCT++, are the above-mentioned features. Beside these, FaCT++ makes use of a variety of performance-enhancing strategies, including both well-known (such as absorption and model merging) and freshly created techniques (such as ordering heuristics and taxonomic classification). FaCT++ supports a tableaux decision method for description logic, as well as datatype support, such as strings and integers [117].

The following example shows how the FaCT++ Reasoner in Protégé 4.3 works (Figure 3.15):

If we have two disjoint classes: “Actuators” and “Sensors”, and we suppose that we want to attribute the “Device Latency” property (has 0.5 sec) from “Actuators” to the InfraRed sensor TSOP (Thin Small Outline Package), this latter from within its superclass “Sensors” is shown in red when starting FaCT++. This is because the “Device Latency” attribute belongs only to “Actuators”, and this is one reason that makes the two classes “Actuators” and “Sensors” disjoints.

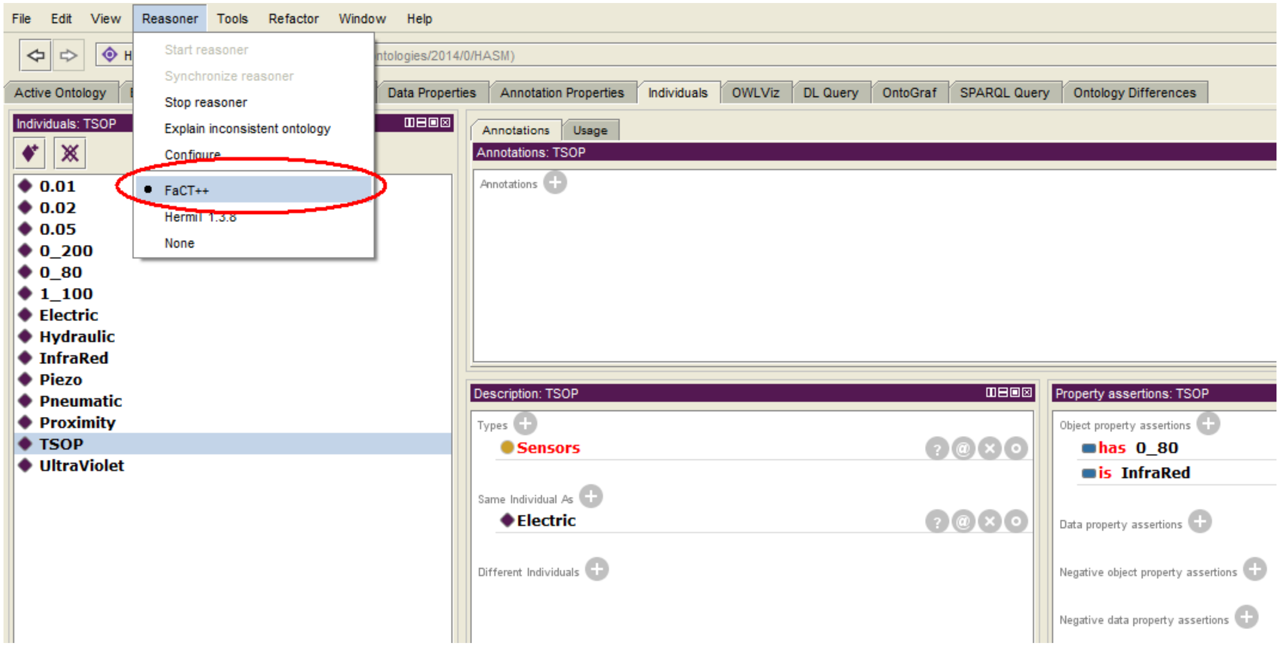


Figure 3.15: Inconsistency with FaCT++ Reasoner in Protégé 4.3

3.4.1.4 - What is next?

Physical attributes, geographical attributes, and temporal attributes were used to categorize the HIS attributes (for each actuators and sensors). SODHO was created using the SUMO model rather than the BFO model as in the HASM ontology, in which the language that characterizes human-haptic system interaction was defined, resulting in a formal classification of the haptics domain that users and applications can use. Second, by incorporating "attributes classes" into SODHO, the haptics ontology will aid in the development of better software for tactile interfaces. This is because, with the proposed unified ontology, we will be working with a global interface that will act as an adapter between the soft service layer and the HIS components. The implementation of the service layer will be made easier as a result of this. Third, data was inferred and processed based on SWRL rules. Fourth, we attempted to tackle the question of how to combine the "real world" and computer media for future Augmented Reality, HAVE, and IOT applications by combining "Actuators" and "Sensors" in one unified ontology.

Next, we introduce KPION-5G, an ontology for 5G networks that we can import it into the “Network Deployment & Platform” module of the OFDTI ontology.

3.5 - Ontology For 5G Networks KPION-5G

Fifth-generation wireless is the most recent iteration of cellular technology, designed to dramatically improve wireless network speed and responsiveness. According to [120], 5G's technological goals include 1000 times more mobile traffic, 10 to 100 times faster user speeds, 10 to 100 times more users, 10 times longer battery life for massive M2M communications, and a five-fold reduction in E2E (End-to-End) delay.

Extreme Mobile Broadband Approach xMBB (Extreme Mobile Broadband), Massive Machine-Type Communication (mMTC), and Ultra Reliable Low-Latency Machine-Type Communication (uRLLC) are the three general services that make up the 5G paradigm. These three common services should be viewed as the foundational qualities for 5G user scenarios.

3.5.1 - KPION- 5G Description

5G is developed to solve 3 modern-day problems [119]:

- ✓ Ultra-low latency: The ultra-low round-trip time that is used to calculate delay after transmitting a packet that is returned to the sender.
- ✓ A massive number of devices communicating with the same access point.
- ✓ Ultra-high throughput: throughput is the rate at which messages are delivered successfully.

Therefore, 5G generic services [137], or main 5G KPIs are divided into 3 classes (Figure 3.16):

- ➢ uRLLC: ultra-Reliable Low-Latency Communication
- ➢ mMTC: massive Machine Type Communication
- ➢ emBB (or xMBB): enhanced mobile BroadBand (or extreme Mobile BroadBand)

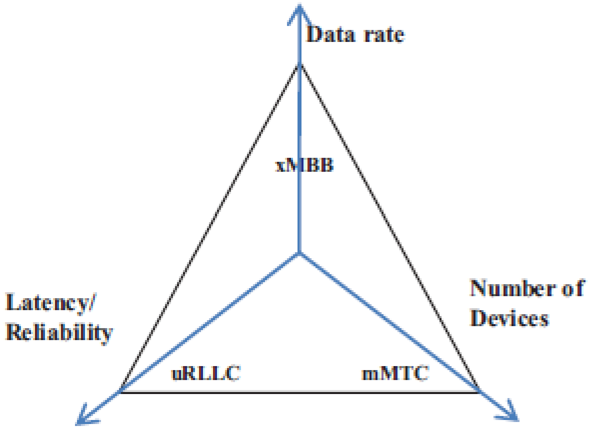


Figure 3.16: 5G generic services [136]

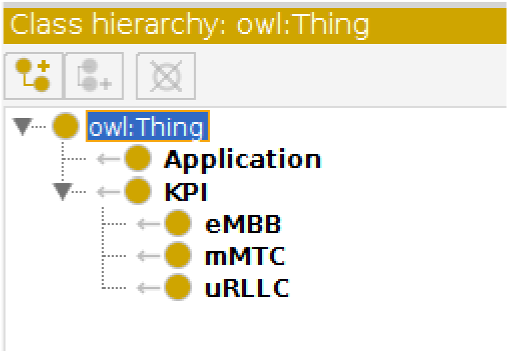


Figure 3.17: Main KPIs Classes in KPION-5G

These are 3 subclasses of the class KPI in the KPION-5G ontology:

New Applications are classified based on their requirements: like low latency, high data consumption and multiple devices (i.e. Tactile Internet applications).

Individuals of the Class "Application" are directly linked to the KPIs mentioned earlier by the relation: "requires" in the proposed ontology.

Some of the KPIs which we mentioned in our Ontology, along with their description, are presented

in the table 3.4 below (we recall some of their definitions from paragraph 3.3.1):

The main applications among those mentioned in the Ontology are listed below:

- Tactile Internet/Augmented reality
- Remote automated parking
- Moving hotspots
- Cloud services
- Smart office
- Device remote controlling
- Disaster alert
- Healthcare

- Airplanes connectivity

KPION-5G Key Performance Indicators(KPIs)	**Description**
Latency	The total of a packet's transmitting delay (at the MAC layer), propagation delay, and waiting time is the End-to-End latency
Data rate	The amount of data sent from the sender to the receiver is also known as the data transmission rate, or simply, data rate. Bits/second, bytes/second or even packets/second, are the most common units of measurement
Reliability	The total number of packets transmitted divided by the number of packets successfully received by one end node (percentage).
Availability	The time the communication system can give service to the user divided by the total period the services are expected to be delivered
Data utilized per frame	Up to 1500 bytes of data are contained in each frame. A frame must have at least 46 bytes of data, even if this implies that the host must pad the frame before sending it. This minimum frame size is required because the frame must be lengthy enough to detect a collision
Connection density (User/Km^2)	The number of connected mobile devices per Km^2
Traffic density (Gbps/Km2)	The total offered load of the connected devices per Km^2
Communication range	In a wireless network, it is defined as the maximum distance over which two antennas may communicate
Mobility	The rate at which a user requests services from a network provider
Download rate	The data rate of the downlink channel
Upload rate	The data rate of the uplink channel

- Wireless Cloud-Based office

- Media on Demand

Table 3.4: Some of KPION-5G KPIs

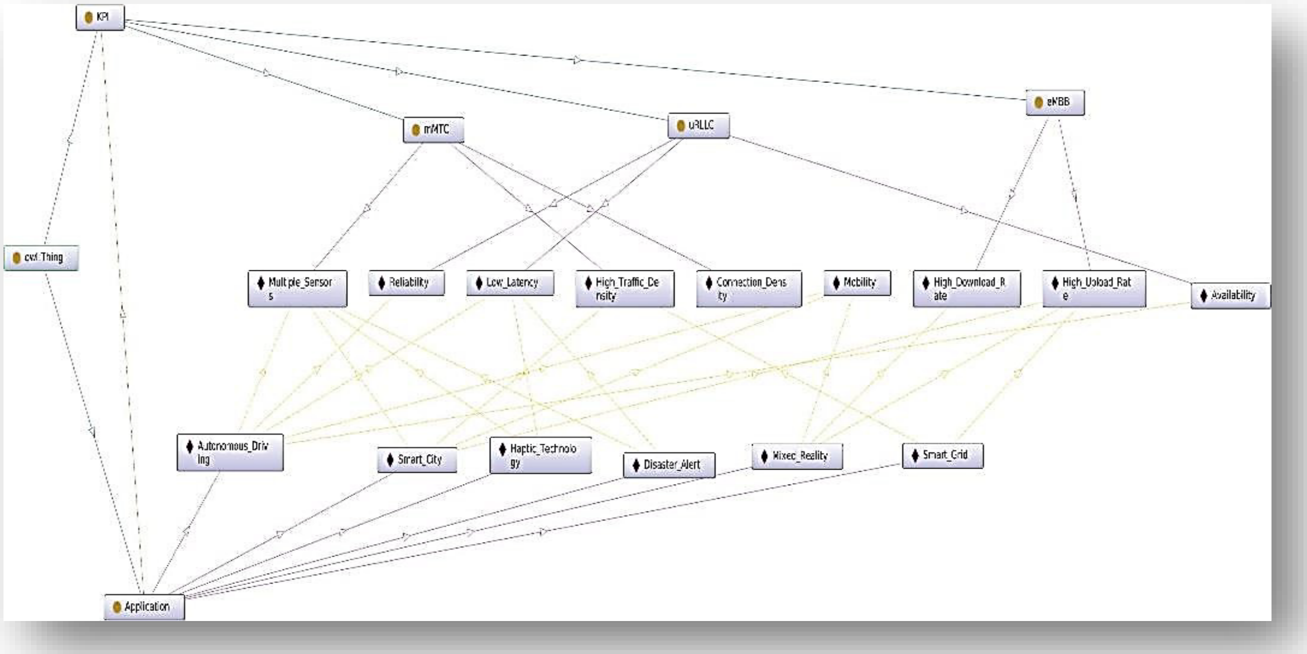
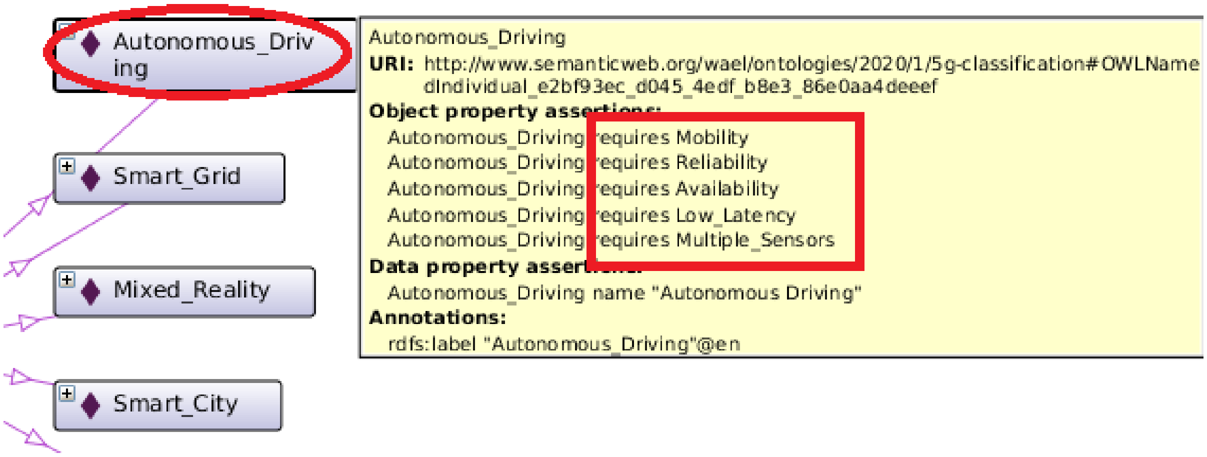


Figure 3.18: KPION-5G Ontograph that represents 5G Applications and their related KPIs

The following KPION-5G ontograph (Figure 3.18) summarizes the relationship between 5G network applications and their main key performance indicators [120].

By selecting any application, we get the list of its required KPIs, as seen in the following Figure 3.19.



Autonomous_Driving
URI: http://www.semanticweb.org/wael/ontologies/2020/1/5g-classification#OWLNamedIndividual_e2bf93ec_d045_4edf_b8e3_86e0aa4deeef
Object property assertions:
Autonomous_Driving requires Mobility
Autonomous_Driving requires Reliability
Autonomous_Driving requires Availability
Autonomous_Driving requires Low_Latency
Autonomous_Driving requires Multiple_Sensors
Data property assertions:
Autonomous_Driving name "Autonomous Driving"
Annotations:
rdfs:label "Autonomous_Driving"@en

Figure 3.19: Objects and Data properties in KPION-5G

At the beginning, two main classes were created (Class1: Applications and Class2: KPIs). KPIs have subclasses where each class contains individuals (each individual represents a range of values or specific value of related KPI). In data properties, some variables are created where each one defines an individual inside each class. After defining an individual (application in this case), we select the class which is related to. And the relation is selected as well to highlight the KPIs that it requires (by using the already defined relation in object properties: REQUIRES).

3.5.2 – Discussion: Relationship between DT/TI Applications and Their Requirements

In this work, we recall that the major goal is to find the most suitable or optimal network type for given DT/TI applications based on their natures and requirements. We mean by optimal, the set of methods and rules that are able to accommodate the applicability of the DT/TI systems (here come the applications KPIs) in an acceptable environment or infrastructure (here come the networking's KPIs). Therefore, we modeled our OFDTI ontology, and used Protégé (which is an OWL Web Ontology Language emulator [165]) to infer, from the obtained results, the adequate network type to be used for a specific application of Digital Twin and Tactile Internet.

After that we presented the model of OFDTI, and the two ontologies: SODHO and KPION- 5G, the applications were classified due to their requirements, and the networks infrastructures were grouped into five network type classes: 5G, 4G LTE-A, 3G, WiMAX, and

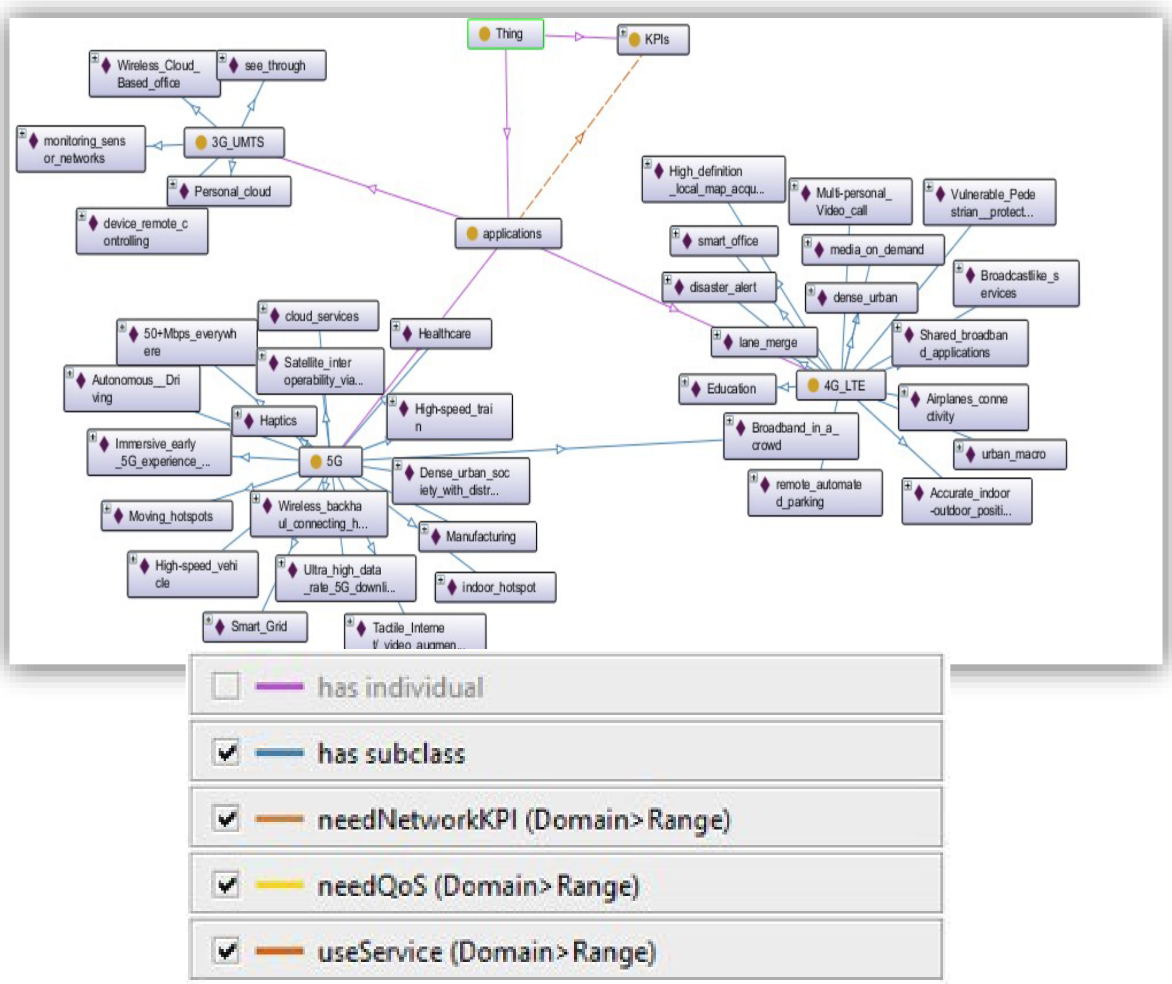


Figure 3.20: Part of OFTDI Ontograph which links a given Application (with specific KPI) to one of the three network type 3G, 4G, and 5G

Wi-Fi. Now, any application in specific network subclass relates to an individual value of the needed KPIs (because to space constraints, portions of the ontology are shown in the following Figures 3.20).

A particular domain's ideas, proprieties, and restrictions are defined by the low ontology. A low ontology often provides the definitions of the concepts that will be applied in a practical application. A QoS network ontology is used in this work to gradually clarify the ideas that are being discussed. Due to space visibility constraints, we figured this Ontology in the Appendix. At this level, a desired QoS Metric Function instance can be constructed, with the component metrics' attributes and the resultant metric's properties specified. In this manner, an ontology can directly specify domain-specific QoS knowledge.

Finally, the full ontology is created, and now it’s clearly shown for each type of application, the necessary list of requirements and the Network type which may cover these conditions. We can see below (Figure 3.21), the ontology which lists all available applications for each network type, and links us to specific KPIs.

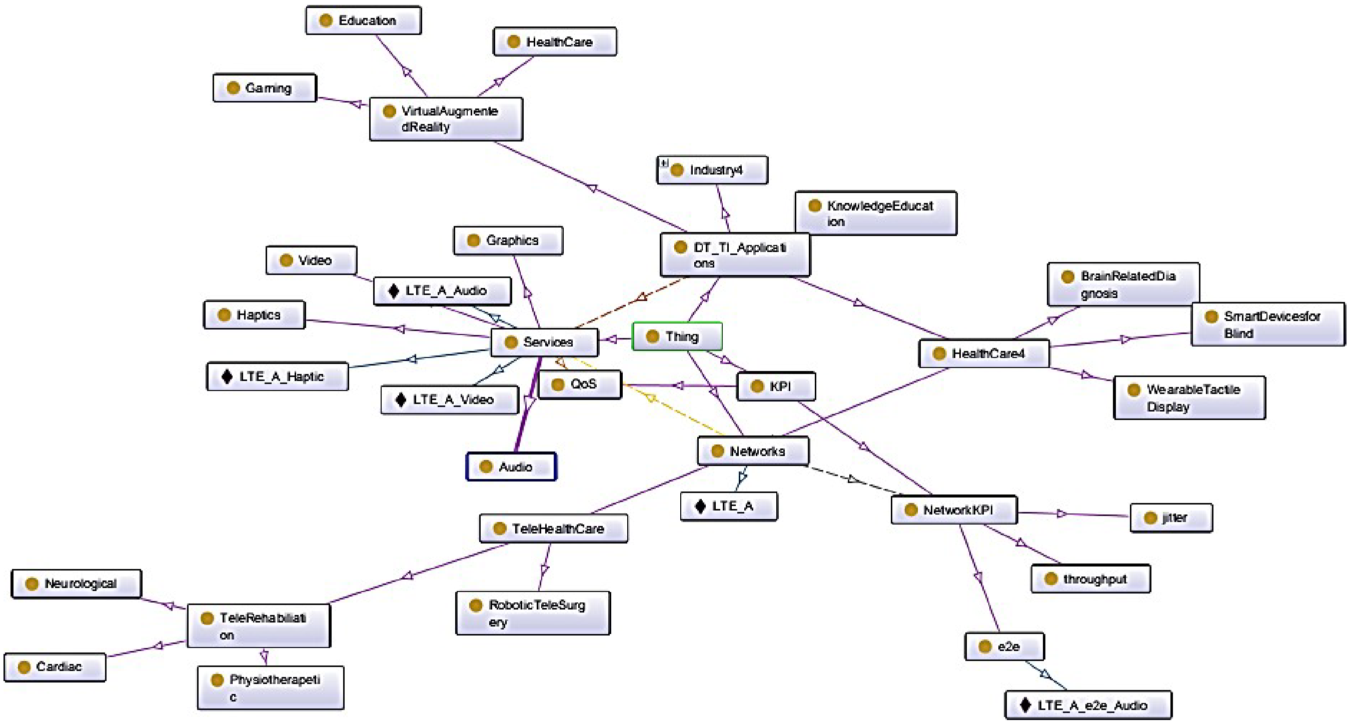


Figure 3.21: Ontograph of OFDTI

3.6 - OFDTI Fuzzy Information System

Knowledge can be used by reasoning engines, such as rule-based systems, to construct the behavior model and constrain the test cases. Test cases are organized into test suites, and a test plan specifies how tests are

run, such as sequential, concurrent, or process forking.

We designed a Fuzzy Information System (FIS) for OFDTI on a model-based approach. This system is intended to validate three conducted applications test cases that made the subject of Chapter 4, and therefore, to infer the most suitable network type for a given DT/TI application with given KPIs. Moreover, it is planned to perform other tasks in further perspective research.

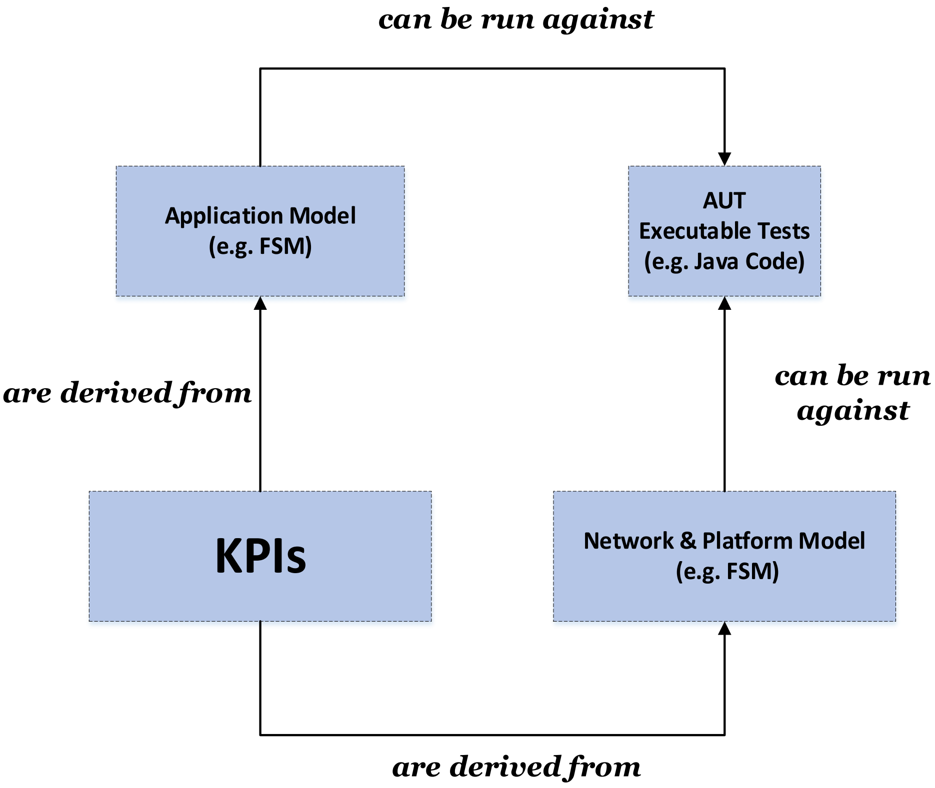
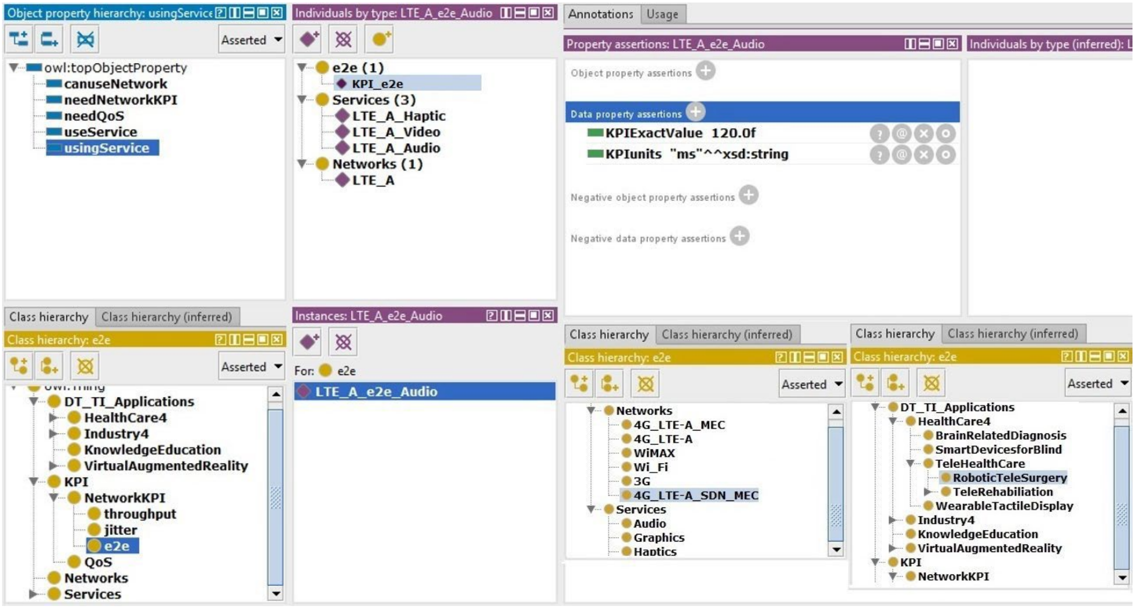


Figure 3.22: OFDTI Fuzzy Information System model

The FIS model gives a rough idea of what the Application Under Test (AUT) is like (see Figure 3.22). Finite state machines [166] are a good way to model testing behavior. Following that, a route search algorithm can analyze the fuzzy rules and construct a plausible test case from each path through the FSM, defining the abstract tests, as stated in TTCN-3 [167], along with the test data. The fuzzy rules are based on the "*is a*" properties connections, and on "*if- Then-Else*" class, which is a control construct, where "*IfCondition*",

"*Then*", and "*Else*" are properties that hold distinct components of the "*if-Then-Else*", and its semantic is set as "*Test If-condition; if True do Then, if False do Else*". For example, we were able to prove that: "*if Application is a* ***RoboticTeleSurgery*** *and has* ***KPI_e2e*** *= 0.5 ms, Then Network is a* ***4G_LTE-A_SDN_MEC***" (Figure 3.24). This result was expected as the simulations conclusion of the test cases conducted over Riverbed in the next chapter. We also can match many simulation results with the ones from the FIS output. Finally, within the TTCN-3 test framework, the TTCN-3 test cases are compiled and performed on the AUT test environment.

Because high-level business services and applications that use DT/TI data need to monitor them in order to choose more reliable and quality DT/TI services, QoS becomes more important. It also acts as essential criteria for service adaption and re-composition decision- making. Because the values of QoS parameters are continually changing as the physical environment changes, robust monitoring systems for DT/TI services and applications are required. When there are a high number of DT/TI service instances, this may become unworkable or inefficient. To generate events and alter the values of QoS parameters, more scalable approaches such as event reporting and complicated event processing techniques can be employed instead of monitoring DT/TI services and applications.



KPIExactValue 120.0f
KPIunits "ms"^^xsd:string

Figure 3.23: Example of robotic Tele-surgery application type with its KPIs requirements in Protégé

In the following subsection, we present our best endeavor to realize our proposed ontology model via Session Description Protocol.

3.7 – Enabling the Taxonomy Using SDP

In the era when audio and video communications are universal and popular, the real-time audio/video conferencing needs the protocols like RTP (Real-Time Transport Protocol),

RTSP (Real Time Streaming Protocol), RTCP (Real-time Transport Control Protocol),etc.

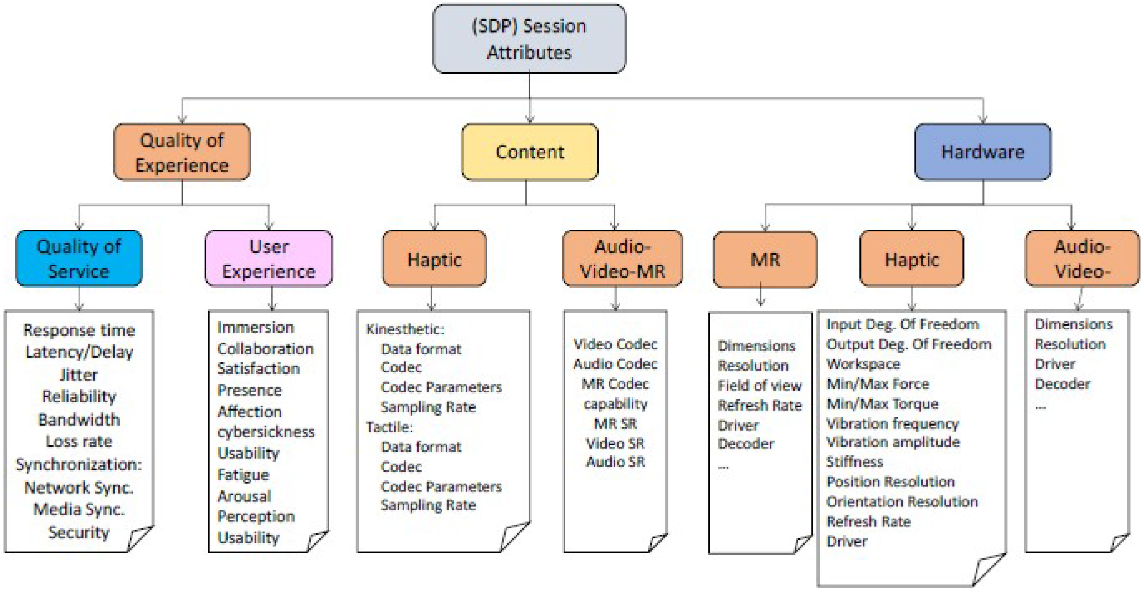


Figure 3.24: Higher level DT QoE/QoS Taxonomy

while push and pull streaming over the network. Session Description Protocol (SDP)

[121] provides a standard demonstration for defining multimedia sessions for the objectives of session declaration, session invitation, and session creation. This incorporates media and transport information (e.g., media kind, media format, transport protocol used), a high-level session overview (e.g., session name, goal, privacy), and so on. The choice of which transport protocol and session control protocol to use, as well as how to use them, is implementation-specific, as it is determined by the needs of the application and the requirements of the service provider. Hence it can be a practical tool that supporting the use of the aforementioned transport protocols and can be extended to support handshaking session between the master and slave in a Haptic Mixed reality teleoperation scenario, Figure 3.24.

It can be used to make haptic interfaces work on the tactile internet as a “Plug- and-play”. Further, it can be extended to supported the exchange Codec capabilities for heterogeneous haptic interfaces as well as the exchange/setup any other information (such as QoE parameters) that might be relevant to the DT application. SDP is proposed by the Internet Engineering Task Force (IETF), which is the maker of various standards of the network. The IETF contains a number of specific task groups, of which the Multiparty

Multimedia Session Control (MMUSIC) working group defines the famous SDP, SIP and RTSP [122]. SDP is completely a session description format (corresponding to RFC2327) [123], and it is also a text-based protocol, using the UTF-8 encoded ISO

10646 character set, which ensures that the protocol is more scalable and makes it a wide range of applications. The main purpose of SDP is to inform the existence of the session and give the necessary information to allow users to participate in the session. However, the allocation of multi-cast addresses and the transmission of SDP messages are not defined, and the negotiation of the media coding scheme is not supported. These functions are all completed by the underlying transport protocol. There are some main description lines introduced below:

”v=”: gives the version of SDP;

”s=”: shows the session name, each session description must include one and only one session name;

”o=”: gives the originator (initiator) information (username, host address) of the session, as well as the session ID and session version number.

A specific form could be: o= <username><session id>>version><network type><addresstype><address>. The quintuple (not include the >version) forms a globally unique session identifier, among them:

- <username>: displays the name of the user that logs in on the initiating host;
- <session id>depending on the session description creation tool to assign a string of numbers, and it’s recommended that use an NTP timestamp to ensure the uniqueness;
- <network type> using a text string to give the network type, for example, ”IN” refers to ”Internet”;
- <address type> using a text string to give the address type, for example, ”IP4” or ”IP6”;
- <version>the version of the session description which depends on the session description creation tool, as long as the <version>is incremental when modifying the session data;

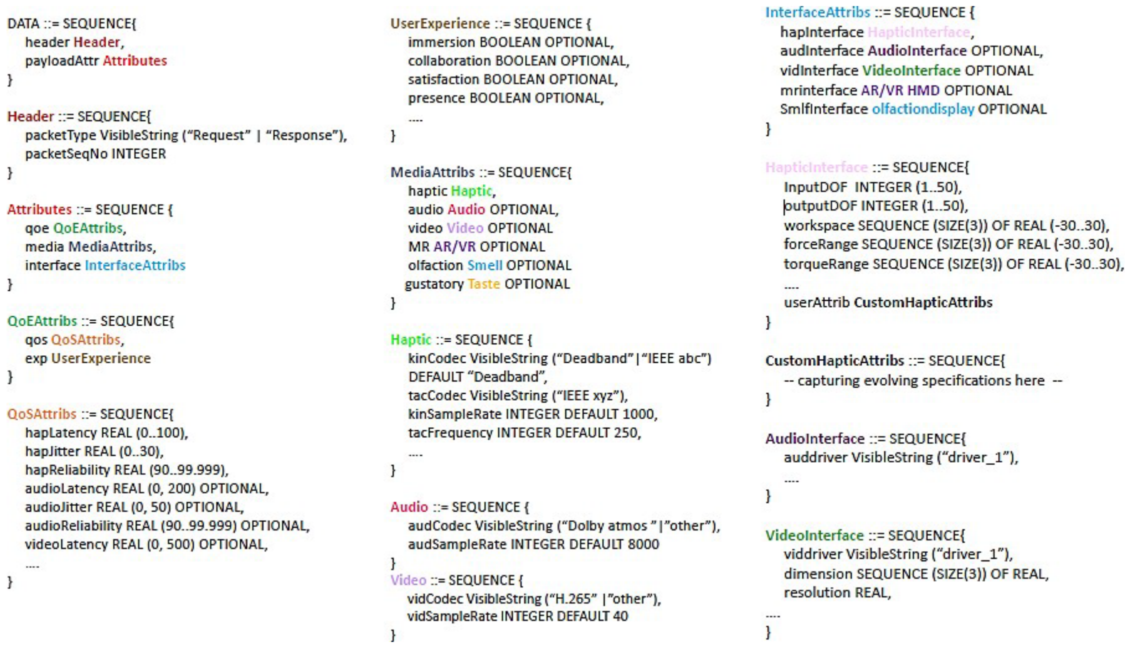
”c=”: lists the connection parameters, c= <network type><address type><connection address>

- <network type> specifies the network type, for example, ”IN” refers to ”Internet”;
- <address type> allows SDP to be used for sessions that are not IP-based, currently, only IP4 is defined;
- <connection address> depending on the value of <address type>domain, an optional additional sub-domain can be added after the connection address. When the address type is IP4, the typical connection address will be the IP multicast group address of class D. It’s indispensable to add a Time to Live (TTL) of the session after the IP multi-cast group address separated by a slash, and the TTL’s values range from 0 to 255. The TTL and IP multi-cast group address together define the range of multi-cast packet transmission in the session.

”m=”: a description of the media stream, m=<media><port><transport><fmtlist>;

- <media>specifies the type of media;
- <port> indicates the transmission port for media streaming acceptance. The meaning of the value of the transmission port is different according to the transmission protocol given in the following 'transport'. For instance, for UDP based port, its port values range from 1024 to 65535; for RTP-based, it has a pair of ports: one for the RTP packet and one for the RTCP packet, so that the RTP/RTCP data can be sent correctly. The RTP data is sent to the even UDP port, and the corresponding control signal RTCP data is sent to the adjacent odd UDP port

- <transport> identifies the transport protocol and the value of it depends on the address type of the "c=". For IP4, most media streams are delivered over RTP/UDP;



```
DATA ::= SEQUENCE{
   header Header,
   payloadAttr Attributes
}

Header ::= SEQUENCE{
   packetType VisibleString ("Request" | "Response"),
   packetSeqNo INTEGER
}

Attributes ::= SEQUENCE {
   qoe QoEAttribs,
   media MediaAttribs,
   interface InterfaceAttribs
}

QoEAttribs ::= SEQUENCE{
   qos QoSAttribs,
   exp UserExperience
}

QoSAttribs ::= SEQUENCE{
   hapLatency REAL (0..100),
   hapJitter REAL (0..30),
   hapReliability REAL (90..99.999),
   audioLatency REAL (0, 200) OPTIONAL,
   audioJitter REAL (0, 50) OPTIONAL,
   audioReliability REAL (90..99.999) OPTIONAL,
   videoLatency REAL (0, 500) OPTIONAL,
   ....
}

UserExperience ::= SEQUENCE {
   immersion BOOLEAN OPTIONAL,
   collaboration BOOLEAN OPTIONAL,
   satisfaction BOOLEAN OPTIONAL,
   presence BOOLEAN OPTIONAL,
   ....
}

MediaAttribs ::= SEQUENCE{
   haptic Haptic,
   audio Audio OPTIONAL,
   video Video OPTIONAL
   MR AR/VR OPTIONAL
   olfaction Smell OPTIONAL
  gustatory Taste OPTIONAL
}

Haptic ::= SEQUENCE {
   kinCodec VisibleString ("Deadband"|"IEEE abc")
   DEFAULT "Deadband",
   tacCodec VisibleString ("IEEE xyz"),
   kinSampleRate INTEGER DEFAULT 1000,
   tacFrequency INTEGER DEFAULT 250,
   ....
}

Audio ::= SEQUENCE {
   audCodec VisibleString ("Dolby atmos "|"other"),
   audSampleRate INTEGER DEFAULT 8000
}
Video ::= SEQUENCE {
   vidCodec VisibleString ("H.265" |"other"),
   vidSampleRate INTEGER DEFAULT 40
}

InterfaceAttribs ::= SEQUENCE {
   hapInterface HapticInterface,
   audInterface AudioInterface OPTIONAL,
   vidInterface VideoInterface OPTIONAL
   mrinterface AR/VR HMD OPTIONAL
   SmlfInterface olfactiondisplay OPTIONAL
}

HapticInterface ::= SEQUENCE{
    InputDOF  INTEGER (1..50),
    outputDOF INTEGER (1..50),
    workspace SEQUENCE (SIZE(3)) OF REAL (-30..30),
    forceRange SEQUENCE (SIZE(3)) OF REAL (-30..30),
    torqueRange SEQUENCE (SIZE(3)) OF REAL (-30..30),
    ....
    userAttrib CustomHapticAttribs
}

CustomHapticAttribs ::= SEQUENCE{
    -- capturing evolving specifications here  --
}

AudioInterface ::= SEQUENCE{
    auddriver VisibleString ("driver_1"),
    ....
}

VideoInterface ::= SEQUENCE{
    viddriver VisibleString ("driver_1"),
    dimension SEQUENCE (SIZE(3)) OF REAL,
    resolution REAL,
....
}
```

Figure 3.25: Schema for XML Handshake Packet: Request/Response

- <fmtlist> gives a list of formats for media, usually includes the media payload type. When a list of formats is given, that implies the format specified therein may be used for this session;

The authors in [124] extended the features of SDP by incorporating Tactile Internet Metadata (TIM) scheme which is a haptic handshake protocol that facilitates the ex- change of haptic metadata between TI nodes. Till now, DT steps into the multimodal interaction environment, the entity can get involved in the virtual reality through wearing the VR glasses or interact with other remote entities by haptic instruments and other wearable devices (e.g. hug jacket). With the help of Quality of Experience (QoE), which could perform as feedback in an XML-based file as shown in Figure 3.25, the Digital Twin system can optimize the overall perception.

3.8 – Conclusion

In this chapter, we presented an ontology-based framework for DT/TI applications - **OFDTI**, a modular ontology, into which we can import two developed ontologies, one for haptics – **SODHO** (especially for sensors and actuators), and the other – **KPION-5G**, a preliminary ontology that relates the future 5G applications to their required network key performance indicators. This ontology is the first step towards the building of a complete and global ontology that links future Digital Twin/Tactile Internet, and Next Generation Mobile Networks applications to their corresponding KPIs, and therefore allows for networks resources optimization.

In the next chapter, we validate the Ontology outcomes by using test cases over the most deployed wireless networks.

Chapter 4 - Validating ontology outcomes over test cases

Teleoperation, without a doubt, is a rapidly expanding discipline that combines robotics, telecommunications, and data processing.

Various control and communication systems have been developed to solve the issues of haptic communication for time-delayed teleoperation, as discussed in the previous sections. Until now, the control and communication components have been examined mostly in isolation, while crucial properties of the underlying communication network have been abstracted or ignored. Implementing teleoperation systems using real-world communication infrastructure, such as wired or wireless IP networks, necessitates a more holistic approach. To create a reliable, transparent, and efficient system design in real-world packet-switched networks, control and communication issues must be considered together. Furthermore, variable network QoS factors and artifacts brought into the system affect the robustness of state-of-the-art systems.

Haptic interfaces will be used from devices connected to mobile networks, according to current technology trends. As a result, more research into how teleoperation systems might be optimally incorporated into next-generation (5G) mobile networks is required. This includes studying the mobile network infrastructure and developing new protocols and assessment metrics based on precise traffic models to optimize the communication channel.

The present chapter, discusses, through three test cases scenarios, the performance evaluation for the most deployed, wired and wireless networks, regarding the applicability of DT/TI systems. The goal of the test cases is to test the suitability of these networks to carry DT/TI applications with the most required key performance indicators. The three scenarios tackle: one test case for immersed Collaborative Haptic Audio Video Environment (HAVE), with traditional QoS schemes over wired communications, and two test cases for Tactile Internet and Digital Twin applications, the first over Wi-Fi/WiMAX/3G, and the second over 4G-LTE-A boosted by SDN/NFV/MEC. The QoS KPIs assessment schemes, for the three test cases, deal with the most important parameters for delay-sensitive applications (e.g. throughput, end-to-end delay and jitter). The networking environments and networks' topologies are designed using the Riverbed Modeler 18.8 [95], and the simulation results validated the outcomes of the Fuzzy Information System of the developed OFDTI ontology presented in the previous chapter.

4.1 – Traditional QoS Schemes over Wired Communications

Multimedia communication refers to the multiple sensory channels used to convey information that is spatially, temporally, and contextually correlated. For decades, multimedia has been solely based on vision and hearing. Technical solutions related to the acquisition, coding, storing, conveying, and displaying these modalities have reached a remarkable quality level which is typically referred to as high definition (HD) and beyond. On the contrary, concept, and technologies addressing the sense of touch i.e., haptic, have not yet achieved the same level of sophistication. With the emergence of the fifth generation (5G) notation, the designs of the current internetworks will move toward providing a true paradigm shift from content-delivery networks to skillset/labor-delivery networks, and will thereby revolutionize almost every segment of society. This ultimate design of the Internet is referred to as the Tactile Internet, where ultra-responsive, high-bandwidth and ultra-reliable network connectivity enables the conveyance of physical human experiences remotely [2]. In addition, the appending of the sense of touch in multimedia applications induce more thrilling and promising ways of supporting collaboration, co-presence, tele-touching, tele- manipulation, and togetherness in multimedia systems [10]. The authors in [125] demonstrate the applications of haptics in several multimedia fields, such as medicine, military, training, data visualization and arts, education and entertainment. Indeed, the Tactile Internet will definitely add a new dimension to human-machine interaction [126].

Consequently, we conducted a set of experiments to measure the impact of several IP-QoS mechanisms on Haptics-enabled networks' performance.

4.1.1 – QoS for Immersed Chave

Application Layer QoS, Relative Priority Marking, Service Marking, Integrated Services with Resource Reservation Protocol (RSVP), Differentiated Services (Diff-Serv), Multiprotocol Label Switching (MPLS), and Software-defined Networking (SDN), are the most common QoS architectures and protocols recommended by the IETF. So far, these approaches have been used to support the transmission of traditional modalities such as video, audio and graphics.

Few studies have been carried out regarding a specific QoS implementation for multimodal haptic traffic as well as human computer interaction. As a result and as mentioned in [13], the industrialization of 5G faces an arduous task which is to implement the Quality of Experience/Quality of Service (QoE/QoS) required to enable and improve the performance of haptic communication over the internet.

[31] assessed many solutions to transmit haptic teleoperation-telepresence data and found ALPHAN to be one of the best haptic communication protocols. However, there was no evaluation for Alphan, neither at the internet where network resources become shared, limited and changing, nor in a large-scale. Therefore, this work mainly aims to provide a framework capable of minimizing the overall latency, jitter and packet loss of large-scale optic transmission sent over the internet. To this end, a set of experiments and analytical studies were conducted in order to model the Alphan haptic traffic, the goal being to benchmark it in a large scale measuring the impact of several IP-QoS mechanisms on the haptic system performance.

4.1.2 – Haptic Networked Traffic Modeling

We employed an application that is immersed in 3D audiovisual as well as bilateral tactile and kinesthetic codecs to represent haptic network transmission. The Balance Ball game [41], depicted in Figure 4.1.a, is an example of this application. The application was written in C++ and used the OpenHaptics API for haptic rendering. The experiment was carried out at the University of Ottawa's MCR-Lab. Two workstations were used to run the collaborative application. On a 2x Intel Xeon 3.8GHz with 4GB of RAM and an Nvidia GTX 1050TI visual card, the workstations ran Windows platforms. Each workstation was equipped with a Touch X haptic device [127]. Geometry Touch, Inc. created and sold the Touch X haptic devices, which are six degrees of freedom (DOF) positioning and sensing haptic devices. It has a small footprint and can output three degrees of freedom of force. Figure 4.2 shows the technical specifications for the Touch X haptic interface. Two players from each side hold a ball that is put on a large wooden board. Many forces would be felt by a player holding one end of the board, simulating the real-life force sensation. The game entails two users working together to keep a virtual ball balanced on a board using local and distant haptic devices. Each participant uses his or her haptic device to grasp one end of the board and slowly lift it over a virtual pole to a predetermined threshold. The goal is to work together on a trail to keep the board horizontally balanced as much as possible from the start to the finish. Any shift in the horizontal balance will cause the ball to drift away from both players, penalizing both. The players should correct this by applying their judgment in rebalancing the board utilizing force feedback and 3D graphics.

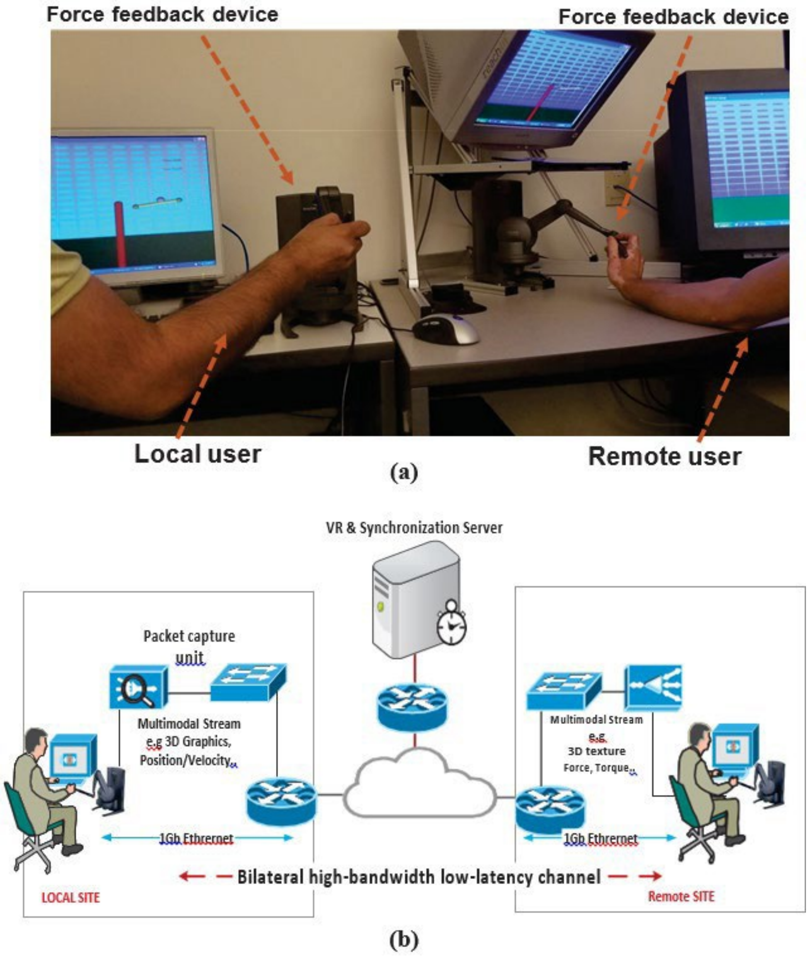
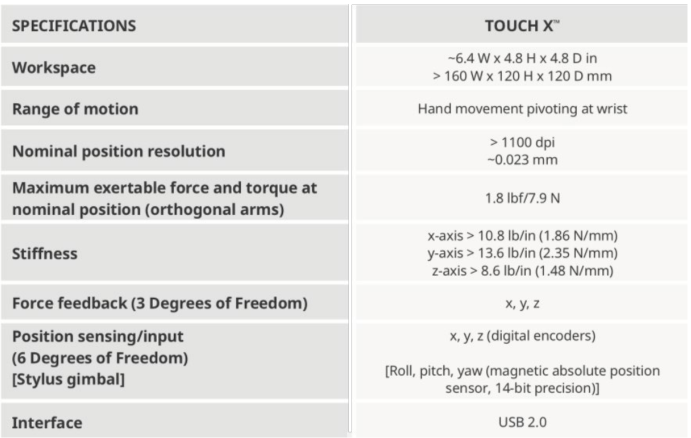


Figure 4.1: Experimental Setup. (a) represents a screenshot of the haptic balance ball game. Two users are interacting haptically with the board, (b) represents schematic model of a multimodal collaborated haptic system over an ultra-low latency Communication Channel



SPECIFICATIONS	TOUCH X™
Workspace	~6.4 W x 4.8 H x 4.8 D in > 160 W x 120 H x 120 D mm
Range of motion	Hand movement pivoting at wrist
Nominal position resolution	> 1100 dpi ~0.023 mm
Maximum exertable force and torque at nominal position (orthogonal arms)	1.8 lbf/7.9 N
Stiffness	x-axis > 10.8 lb/in (1.86 N/mm) y-axis > 13.6 lb/in (2.35 N/mm) z-axis > 8.6 lb/in (1.48 N/mm)
Force feedback (3 Degrees of Freedom)	x, y, z
Position sensing/input (6 Degrees of Freedom) [Stylus gimbal]	x, y, z (digital encoders) [Roll, pitch, yaw (magnetic absolute position sensor, 14-bit precision)]
Interface	USB 2.0

Figure 4.2: Touch X Technical Specifications [183]

We also extended the test bed utilized in the ALPHAN networked haptic protocol, as shown in Figure 4.1.b, to confirm the validity and integrity of our studies. We decided to relocate the haptic transmission process to the Internet, where network resources are shared and changing, rather than executing it on a separate local area network with limited background traffic. Two 1Gbps Ethernet cards were installed on each computer to simulate and mimic the concept of the Tactile Internet. The LAN was implemented using two Cisco 3750 switches, with three Cisco 4431 Integrated Services Routers providing very low latency, high reliability communication channels, and high-bandwidth WAN connectivity. The clocks of the local and remote sites' computers were synced via a Network Time Protocol to prevent unwanted jitter (NTP).

To capture haptic traffic transferred between local and remote sites, each side employed a Riverbed Application Characterization Environment (ACE) module [95], later renamed Steel Central Transaction Analyzer. The haptic traffic traces were used to create a real-world discrete event flow to replicate haptic QoS behavior in a large-scale network using ALPHAN as the haptic communication protocol. The collected haptic model was capable of transmitting roughly 1044 packets per second, as illustrated in Figure 4.3.

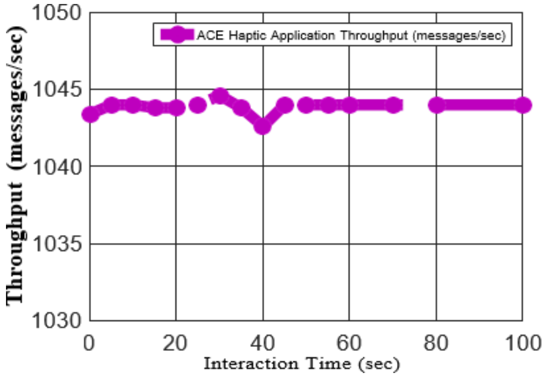


Figure 4.3: The Designed ALPHAN-based Haptic Model's Throughput across a TI Communication System

The static position information is sent at the graphics loop rate of 30 updates per second, while the dynamic position bits of information are provided at the haptic loop rate of 1000 updates per second, which matches the ALPHAN experimental pace. Sending haptic information over a network topology that mirrors the vision of the TI infrastructure, haptic communication should have a very low end-to-end latency (less than 0.208 ms), an ultra-low delay variation of 1 s, and zero data loss, according to Cisco router statistics. The overall quality of perception for haptic users will improve as a result of this. It should be mentioned that when the communication connection between the two players is disrupted, users have experienced an abrupt user experience when utilizing the network emulator. In a summary, Table 4.1 shows the influence of a decreased QoS KPI on QoE in a collaborative haptic VR system. Consumers may experience more force jumps and vibrations in the haptic interface as latency increases. As the impedance of the objects in the remote environment decreases, they may perceive false feedback (stiffness).

Unacceptable QOS metrics	Impact on usability
Throughput	Thrust jumps and sudden movement
Packet Loss	Erroneous and sudden movement of the haptic device
Latency	Decrease user’s feeling and remove collaboration aspect
Jitter	Imbalance of the system

Table 4.1: Impact of QoS disturbance on over all QoE of DT Modalities refined from [183]

4.1.3 - RIVERBED Simulation Scenarios

Riverbed® Modeler [165], formerly known as OPNET Modeler Suite, is a discrete event (DES) simulator commonly used by academic and industrial entities to evaluate networks and assess the influence of various technological designs on end-to-end behavior. Riverbed modeler was chosen over other network simulators because of its ability to leverage real-life captured haptic traffic to construct a better representation application model that offers more precise emulation results. Riverbed also offers various simulation features like as co- simulation, parallel simulation, high-level architecture, and system-in-the-loop interactive simulations, as well as explicit DES and hybrid simulation modes. In a nutshell, riverbed modeler uses an object-oriented modeling method to create models. Node models are network equipment such as routers, switches, firewalls, and so on. Modules are connected by packet streams or static wires in the node model. To achieve the needed behaviors, a process module is assigned to each module. Riverbed's process model uses a finite state machine (FSM) method to facilitate the creation of protocols, resources, applications, algorithms, and queuing policies. The progression of a process as a result of particular occurrences is graphically defined by states and transitions. Each state of a process model has embedded

C/C++ code, which is supported by a large library of network programming functions. Riverbed was viable in developing ALPHAN process model since ALPHAN was implemented in C++, as illustrated in Figure 4.4.

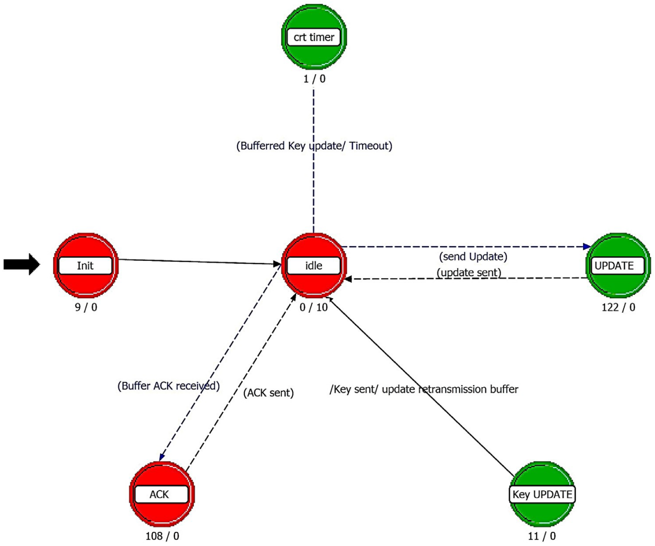


Figure 4.4: Riverbed Process FSM of ALPHAN Sending Module

We used riverbed's network editor to develop a network model to analyze the performance of the ALPHAN haptic transmission model. The "Task Configuration Utility" is used to configure the human-operator and tele-operator workstations to send and receive data through the process model with a throughput of 1044 messages per second, as shown in Figure 4.5. The riverbed ACE module defines discrete event flows that fit the parameters of

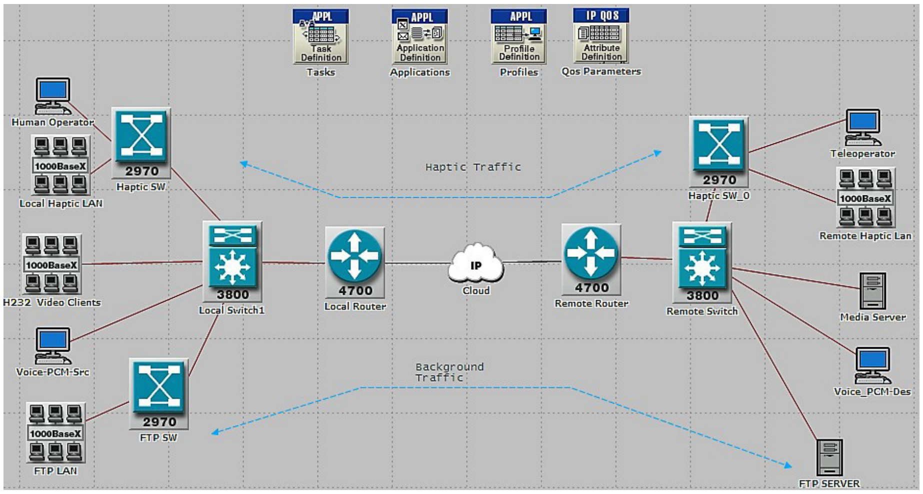


Figure 4.5: Network topology for QoS performance verification of ALPHAN-based Haptic communication Model

the real collected haptic traces, which are then deployed as customized applications and profiles. A large-scale haptic network is created by connecting 28 additional workstations to the local and remote haptic LANs. The IP cloud was built using the Tactile Internet results from the previous part, which included a zero packet discard ratio and low packet latency of 0.1 ms. The other three workstations/LANs are set up to send voice-PCM G.711, video H.264, and file transfer FTP using the built-in applications and profiles. Accordingly. Heavy FTP was represented as an implicit, i.e. background traffic, because our major purpose is to expressly optimize haptic communication.

When different data rates are used, the effect of sending haptic, audiovisual, and background traffic on the local router's resources is shown in Figure 4.6. When the transmission rate is set to 15 Mbps and we ignore the intermittent period, we can plainly see that the router exhausts its resources and reaches maximum utilization. As a result, this is the best data rate for creating a congested scenario that reflects the shared Internet's characteristics. As a result, the bottleneck link is placed just before the local router's output interface, where various types of queuing algorithms are used to maximize the haptic traffic's QoS performance in terms of latency and jitter. We're talking about average end-to-end latency and jitter, which are both measured in milliseconds. We extend our studies to encompass the influence of FIFO, PQ, CQ, and CQ with LLQ on the ALPHAN haptic transmission model, unlike [20], which solely focused on the provision of WFQ and CBWFQ on the haptic stream.

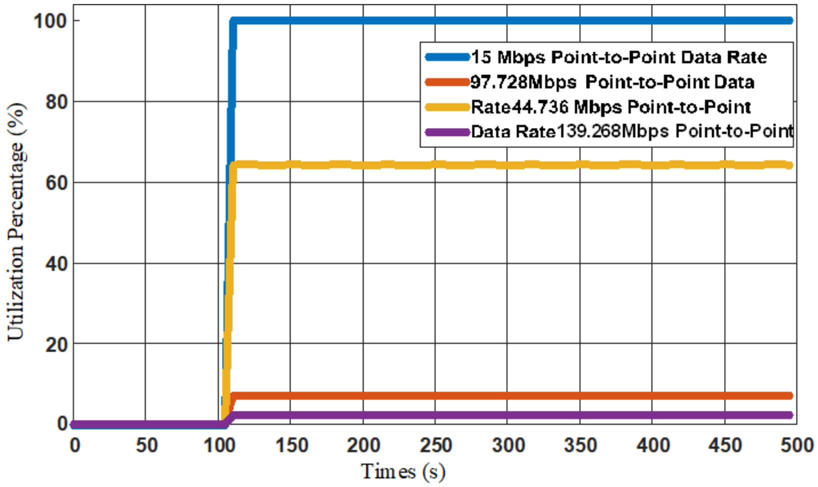


Figure 4.6: Utilization of the local router’s resources when different transmission rate is selected

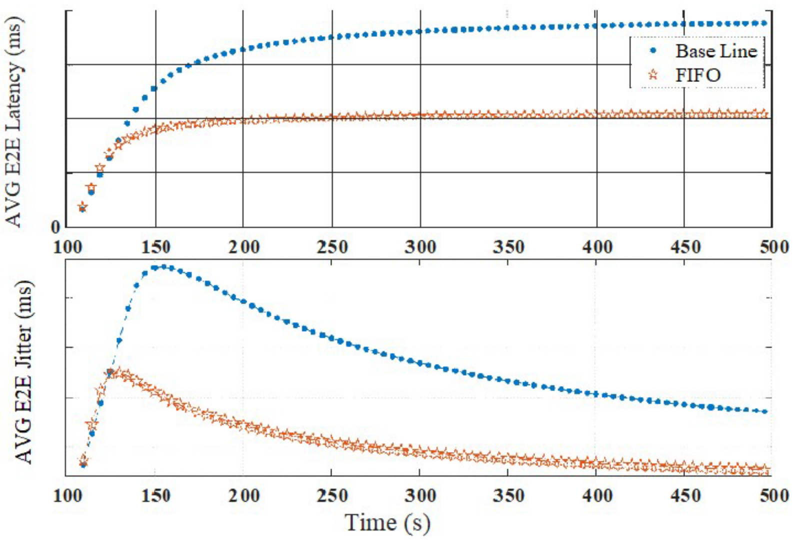


Figure 4.7: End-to-End latency and Jitter of the ALPHAN-based haptic traffic for Best effort and FIFO

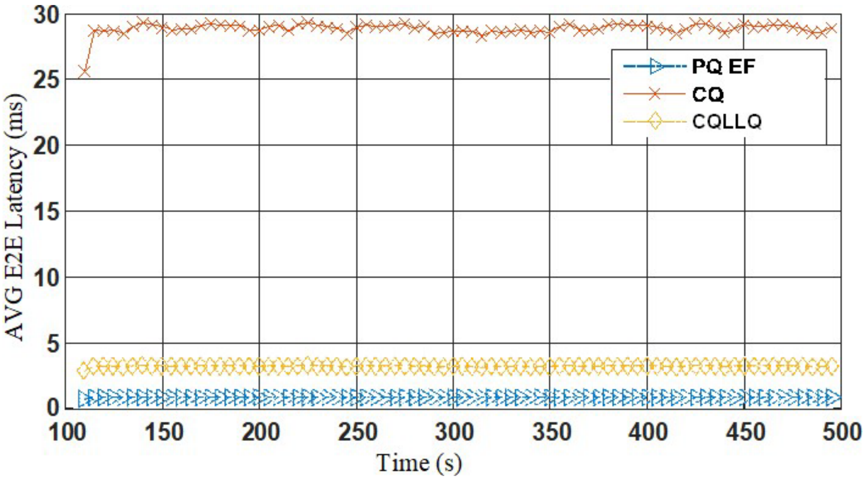


Figure 4.8: Comparison of the impact of CQ, CQ-LLQ and PQ on the End-to-End latency of the ALPHAN-based haptic traffic

Sending haptic data over ALPHAN on a crowded network using the best effort strategy, i.e. no IP-QoS algorithm, will result in high latency and jitter values, as shown in Figure 4.7. When a FIFO with a large queue size is applied to the bottlenecked router interface, performance improves marginally as the haptic stream's latency drops from 800 to 450 milliseconds, indicating a little improvement in the stream's jitter values. Even yet, these findings fall short of the basic requirements for a consistent haptic rendering experience.

Figure 4.8 shows the haptic stream's total latency when PQ, CQ, and CQ with LLQ are used on the bottlenecked router interface. Results for CQ were produced by allocating the haptic queue with the largest byte count among other sorts of services (TOS), such as voice and video. Given that the ALPHAN haptic packet is 74 bytes long (28 bytes payload and header + 8 bytes UDP header + 20 bytes IP header + 18 bytes Ethernet header), we used equations (4.1) and (4.2) to guarantee ALPHAN haptic stream 70% of the 15 Mbps congested bandwidth. The remaining 30% was split evenly between the voice and video TOS queues. Remember that CQ is based on round-robin transmission, therefore if we want more assurance, we may use LLQ to assign the haptic TOS queue the greatest priority possible. Both CQ-LLQ and PQ with expedited forwarding PHB lowered overall latency to 2.54 ms and 1.36 ms, respectively, as shown in Figure 4.8. It should be noted that the jitter values for the aforementioned techniques were extremely low in seconds and can be ignored.

$$CQ_{BYTE_{Count}}(Q_i) = \frac{A * T_r * C}{8 * p} \qquad (4.1)$$

$$\text{BW CQ}_{BYTE_{Count}} = \frac{CQ_{BYTE_{Count}}(Q_i)}{\sum_0^N CQ_{BYTE_{Count}}(N)} \cdot BW\ interface \qquad (4.1)$$

Where *A* is the total packet size of application *i* in bytes, T_r is the transmission rate in bits per second, and *C*: the total number of connections from end to end, *N*: the total number of CQ queues, *P*: the proportionate weight of the packet size of *i* relative to packet sizes from all other *N* queues, *BW interface*: the crowded router's interface's bandwidth capacity.

4.2 – QoS Schemes over Mobile Communications

Now that we explored in the previous paragraph the traditional QoS evaluation over wired Networks, we tackle in the following the QoS evaluation over wireless communication systems, especially those mostly deployed, (i.e. Wi-Fi, WiMAX, 3G, and 4G LTE-A), and give an insight for the 5G deployment.

4.2.1 – Tactile Internet Applications over Wi-FI, 3G and WiMAX: A comparative Study

In this paragraph, different models for Wi-Fi, 3G network (UMTS) and WiMAX networks were designed. The performance of several important parameters such as throughput, jitter, queuing delay and End 2 End delay can be estimated and measured [120].

4.2.1.1 - Methodology

In this work, all network simulations are exclusively realized using the Riverbed Modeler Riverbed is an open source modeling software, which includes tools to build different network models (LAN, WAN, Wired, Wireless, Mobile, Satellite, WiMAX and UMTS), and generates different type of applications (VoIP, video streaming, web browsing, FTP). Using this simulator one can get Global and Node statistics, plot and compare results. Unlike other network simulators, Riverbed modeler [95] was chosen because of its ability to utilize the real-life captured haptic traffic to create a better representation of the application model that gives more precise emulation results.

4.2.1.2 - Simulation of different scenarios

Wi-Fi vs. WiMAX

In this simulation we tried to show the difference of performance in both networks in terms of the distance between users and the access point. Simulations were repeated three times, where in each case the users were moved far away from the base station (1st case 10m, 2nd case 100m, and 3rd case 1000m), in order to discuss the performance of each network as the distance increases. The application used by the users was VoIP. The difference between sent and received packets, throughput, and delay in each network were the main focus of these simulations.

Wi-Fi Proposed Scenario

The scheme of the network topology of this case study is shown in Figure 4.9. In this network we have four subnets, where each subnet consists of one access point and ten nodes. The devices used in this topology are:

- ✓ Wlan_ethernet_slip4_adv and ethernet16_switch
- ✓ Ethernet_server and wlan_wkstn_adv
- ✓ Ethernet2_slip8_firewall.

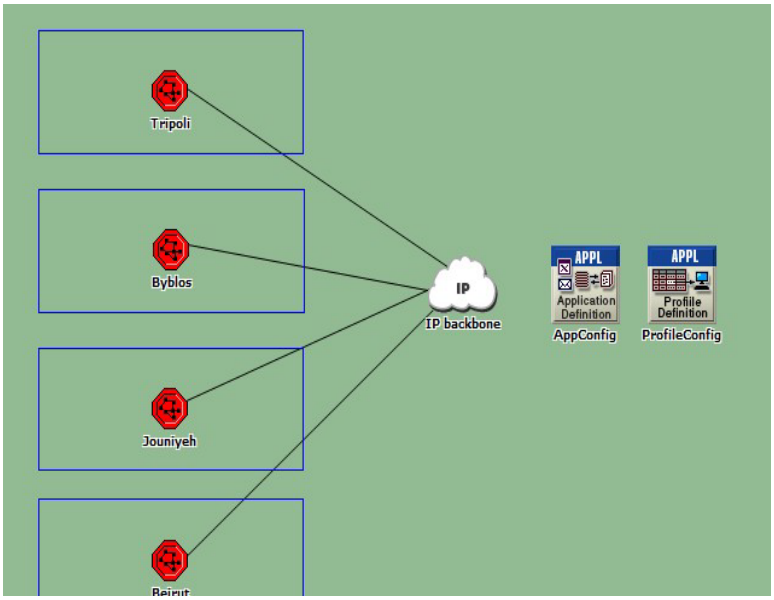


Figure 4.9: Wi-Fi scenario

WiMAX Proposed Scenario

Figure 4.10 below shows the scheme of the network built for WiMAX. Also four subnets were created, where each subnet consists of a base station and ten nodes. The devices that we used in this topology are the following:

- ✓ wimax_bs_ethernet4_slip4_router_adv
- ✓ wimax_ss_wkstn_adv
- ✓ ethernet16_switch
- ✓ Ethernet2_slip8_firewall
- ✓ Ethernet_server.

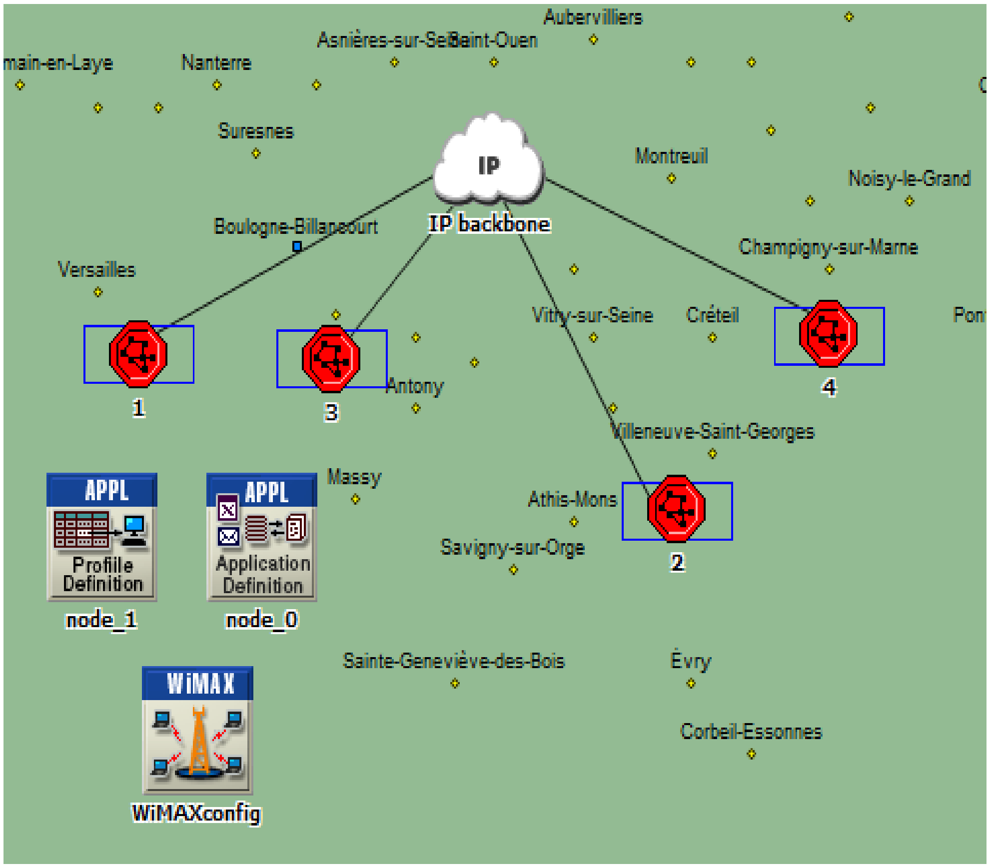


Figure 4.10: WiMAX scenario

Results

- Sent packets vs. received packets:

- At 10m: The Green curve shows packets sent by WiMAX, the red one represents received packets in WiMAX. Dark blue and light blue are two overlapped curves which represent respectively the sent and received packets in Wi-Fi.

- At 100m: in both networks there existed loss of packets but in WiMAX the difference between sent and received packets was lower than that in Wi-Fi.
- At 1000m: there was no loss in the case of WiMAX, while in Wi-Fi 47% of packets were lost.

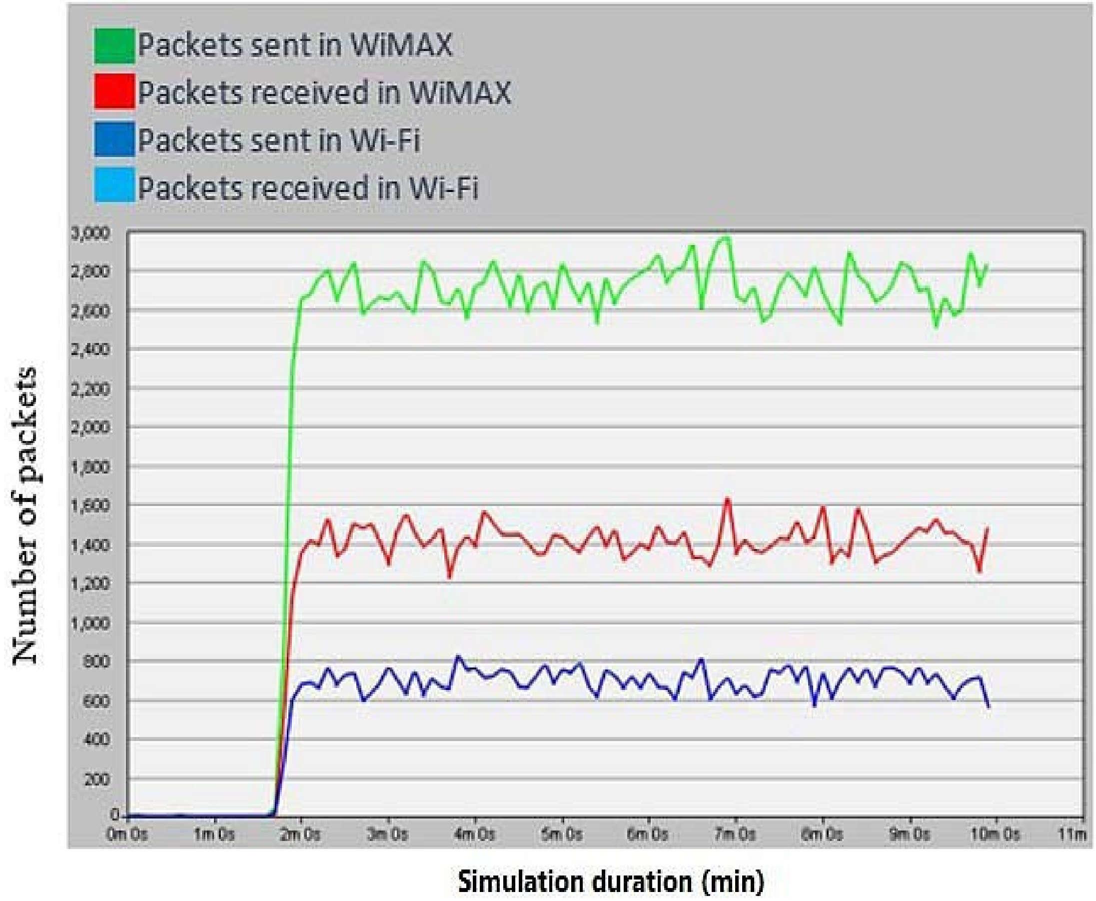


Figure 4.11: Sent packets vs. received packets at 10m

- ➢ ***Throughput:*** in all three cases the throughput in WiMAX was greater than that in Wi-Fi.
- ➢ ***Delay:*** only at 10m, the delay in Wi-Fi was lower than in WiMAX. Starting from 100m

to 1000m WiMAX recorded stable delay (delay of 3 to 4ms). This is an explanation of WiMAX being insensitive to distance variation.

A.WiMAX vs. UMTS

In this scenario, we illustrated the difference of WiMAX and UMTS, when sending different

types of traffics. Three applications were used which are the following: VoIP, video streaming and haptics. In haptics: first case we sent only UDP packets, while in second case UDP with video. As a standard, Haptics stream is modelled by UDP packets of 92 bytes of size (64 bytes for the haptic application + 8 bytes for the UDP header + 20 bytes for the IP header), at a refresh rate of 1000 packets/sec [12]. While high resolution video streaming is sent at rate of 25 frames/sec with 1Mbits Maximum Transfer Unit (MTU). The average delay, throughput, End-to-End delay and queuing delay are the performance metrics used in this work [130].

WiMAX Proposed Model

WiMAX configuration and profile Configuration define and attribute all the applications that are used in this network case study. The proposed WiMAX network model shown in Figure 4.12 consists of five Base Stations; for each cell there exist six mobile nodes to serve all application types mentioned above. A vector-based trajectory is used in this model.

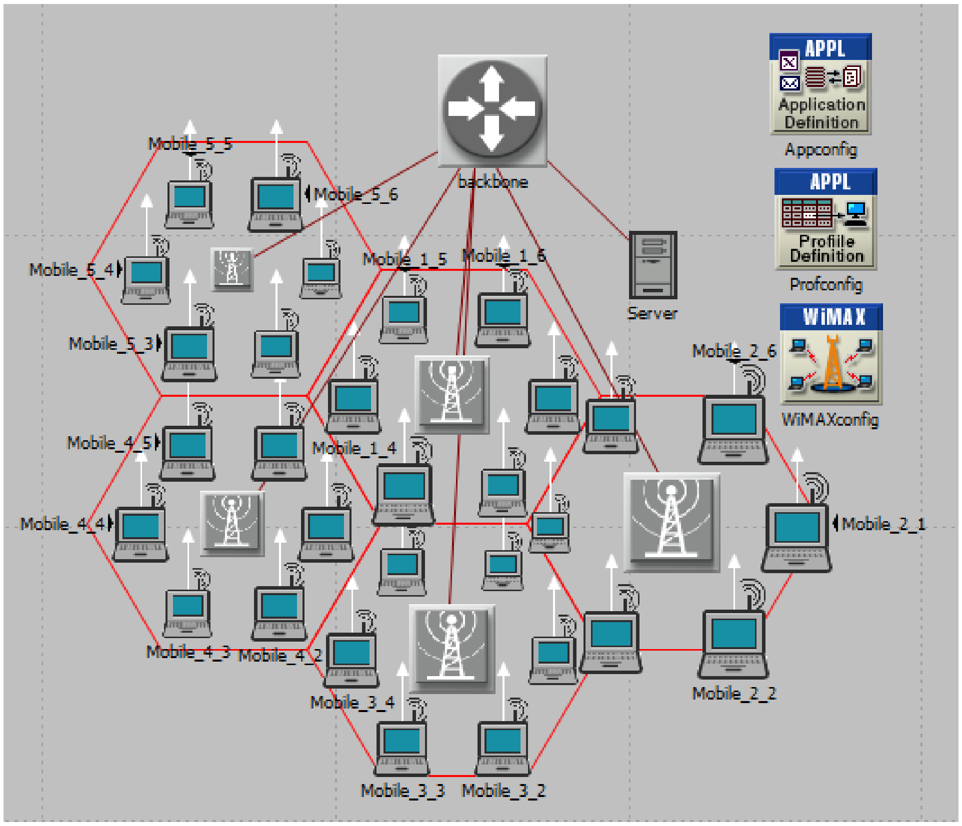


Figure 4.12: WiMAX network

1) ***UMTS Proposed Model***

The proposed model shown in Figure 4.13 consists of 5 BTS and 6 nodes in each cell [131]. It is built up in order to study its performance by running voice, video traffic and haptics; the proposed topology of UMTS network model consists of Node_Bs, RNCs, mobile nodes, routers, servers, and SGSN/GGSN nodes. The coverage area is 10 km * 12 km. A Vector-based trajectory is used in this model. The simulation time in all cases in this paper is taken to be 180 sec.

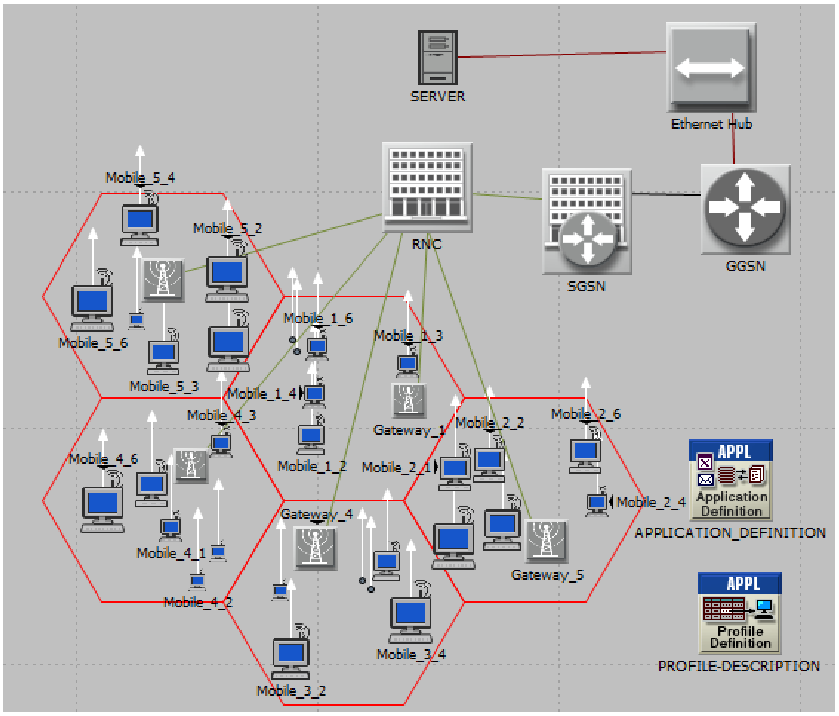


Figure 4.13: UMTS network

2) ***Results***

➢ VoIP:

- Jitter in 3G was higher than in WiMAX. Here we see a peak of 11.5ms in WiMAX and 15.5ms in 3G (Figure 4.14).

- Overall network's delay does not differ too much in both networks.
- Throughput in WiMAX was greater. We can see that the curve's slope in WiMAX was little bit more vertical than that of UMTS.

- Queuing delay in UMTS was 16ms, while in WiMAX was 13ms.

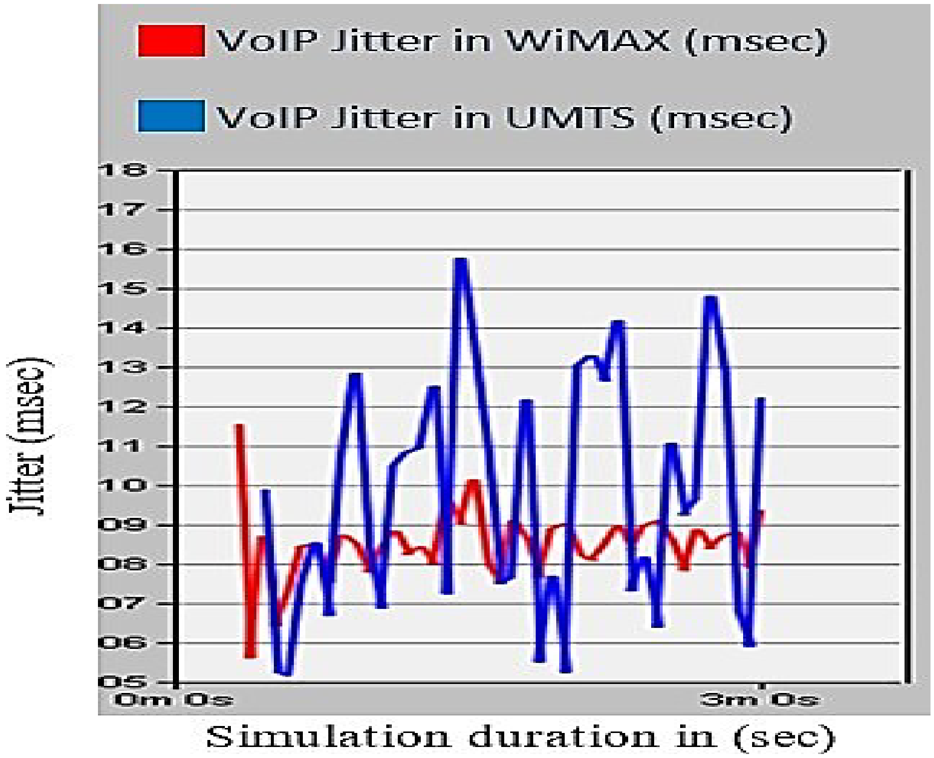


Figure 4.14: Jitter in VoIP in both WiMAX and UMTS

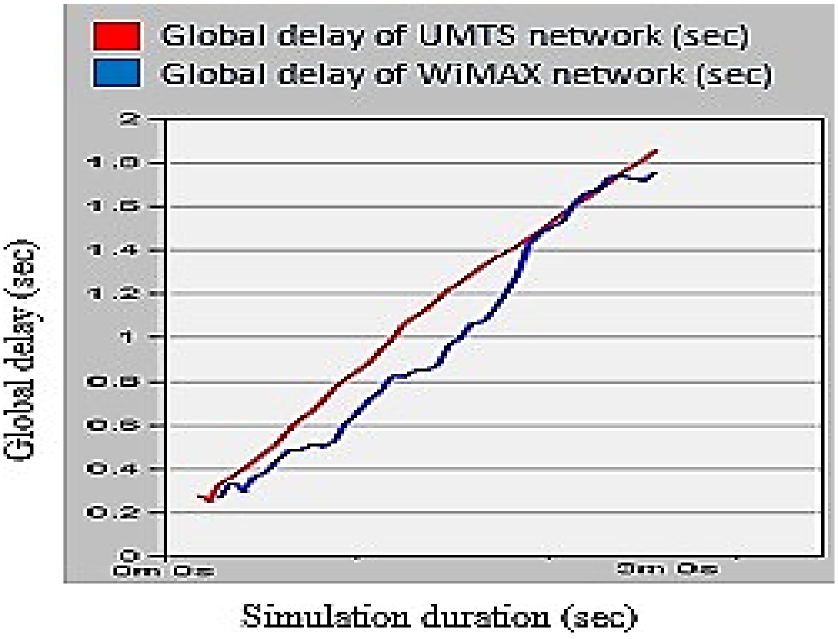


Figure 4.15: Global delay of WiMAX and UMTS when sending VoIP

- ➢ High resolution Video Streaming

The most differences between both networks were in:

- End-to-End delay in WiMAX is 12ms while in UMTS was about 35ms (Figure 4.16).
- Throughput in WiMAX was 55Mbps while it was too much lower in UMTS: 2.5Mbps (Figure 4.17).
- Average delay variation and queuing delay does not differ too much in both networks.

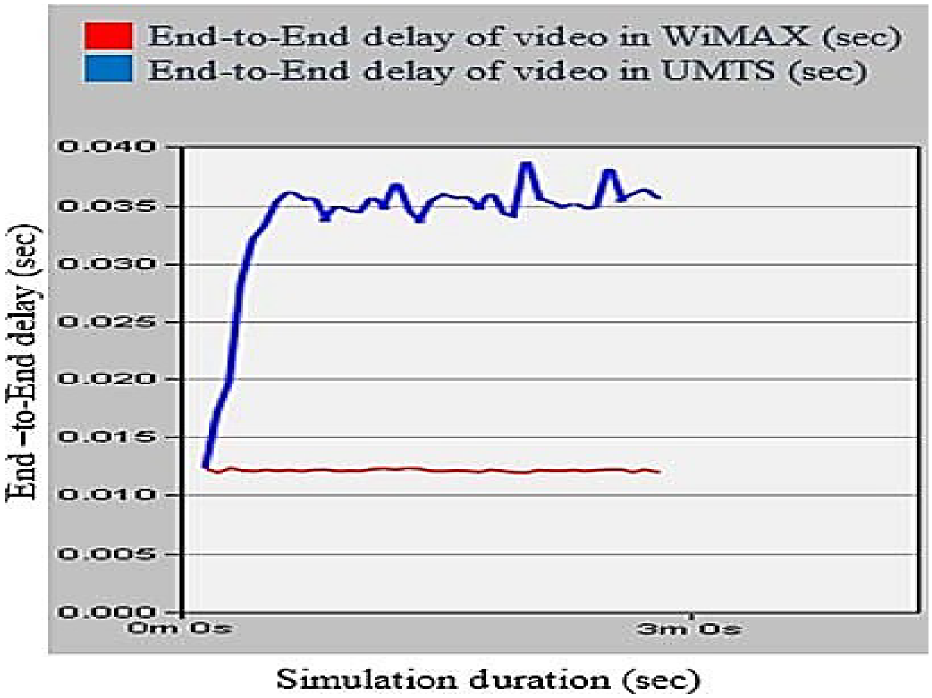


Figure 4.16: End-to-End delay of video in WiMAX and UMTS

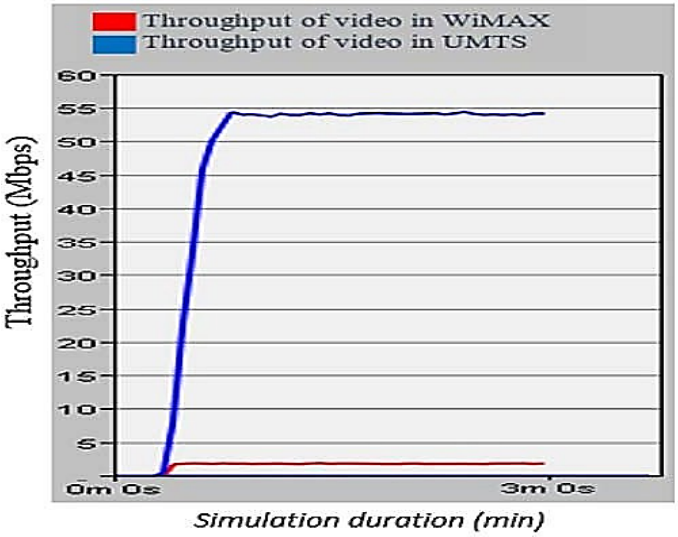


Figure 4.17: Throughput of video in WiMAX and UMTS

- Haptics:

In this case, haptic traffic is sent between an operator and teleoperator, where each one exists in different cells of the network:

- UDP: the End-to-End delay between an operator and teleoperator was 1ms in WiMAX and 15ms in UMTS.
- UDP+Video: the delay was 7ms in WiMAX and 52ms in UMTS.

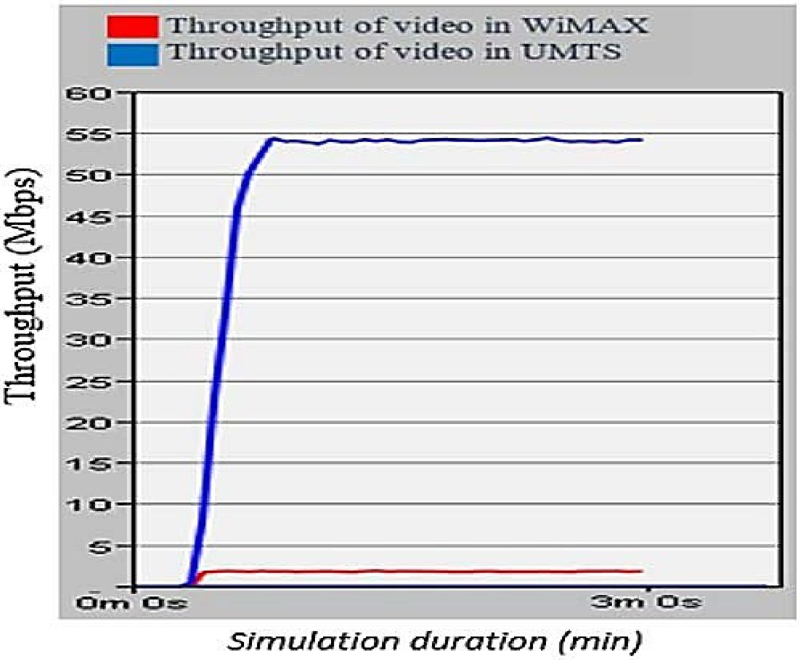


Figure 4.18: End-to-End delay in WiMAX when sending haptics

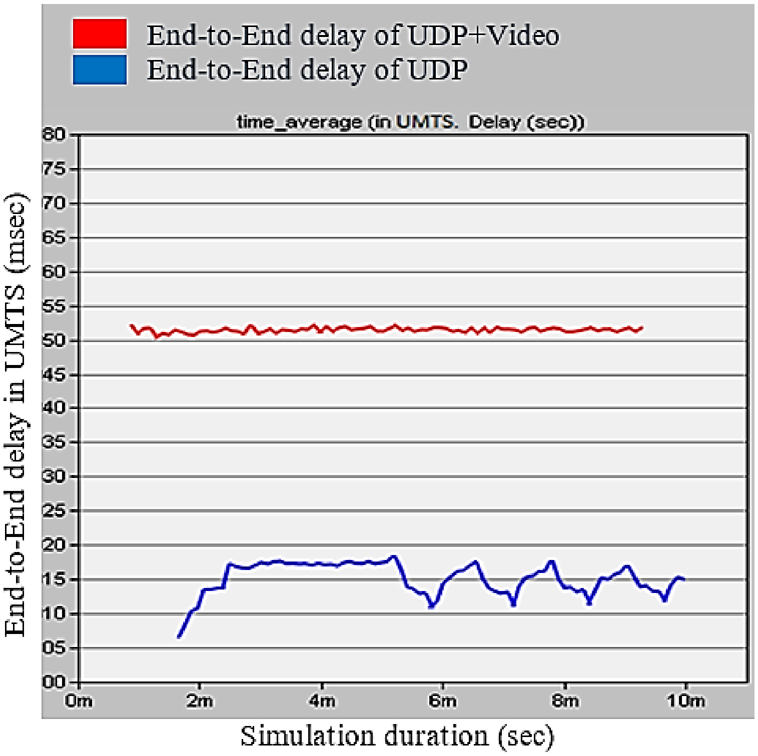


Figure 4.19: End to End delay in UMTS when sending haptics

B.Quality of Service (QoS) in WiMAX

*1) **Overview***

Quality of Service (QoS) is a feature of routers and switches which prioritizes traffic and manages the load by setting priorities for specific types of data on the network so that more important traffic can pass first. In this way we could reduce the packet loss, latency and jitter on the network [132]. In the topology shown below in Figure 4.20, the simulation considers two nodes using two applications (UDP+Video streaming) at the same time. Two scenarios were created: Scenario 1 was without using QoS while scenario 2 was with adding QoS in WiMAX BTS.

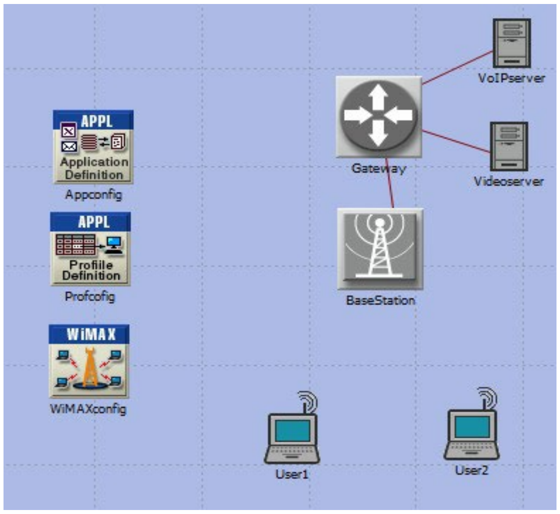


Figure 4.20: Quality of Service in WiMAX

*2) **Results***

Each of the following graphs shows the difference between WiMAX having QoS and WiMAX without QoS.

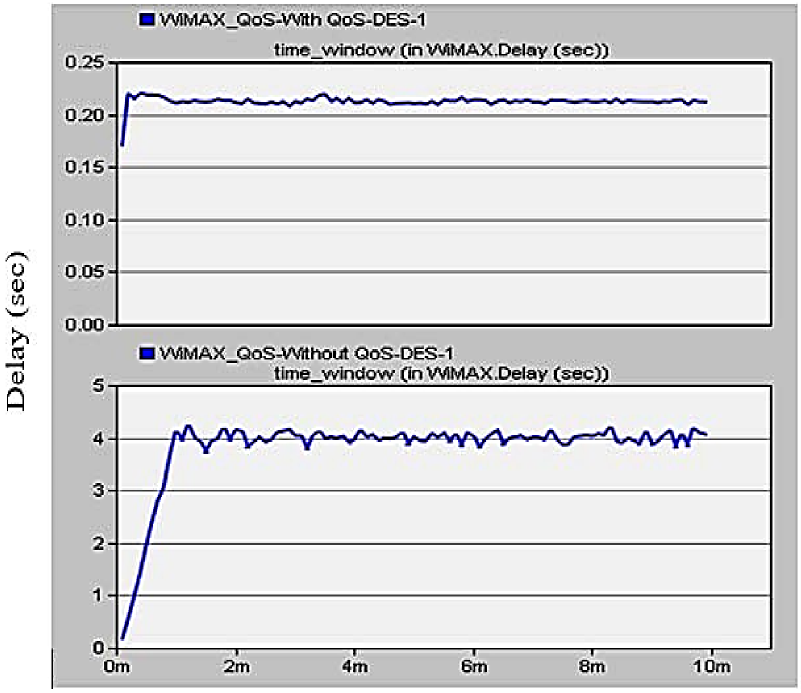


Figure 4.21: WiMAX End-to-End delay

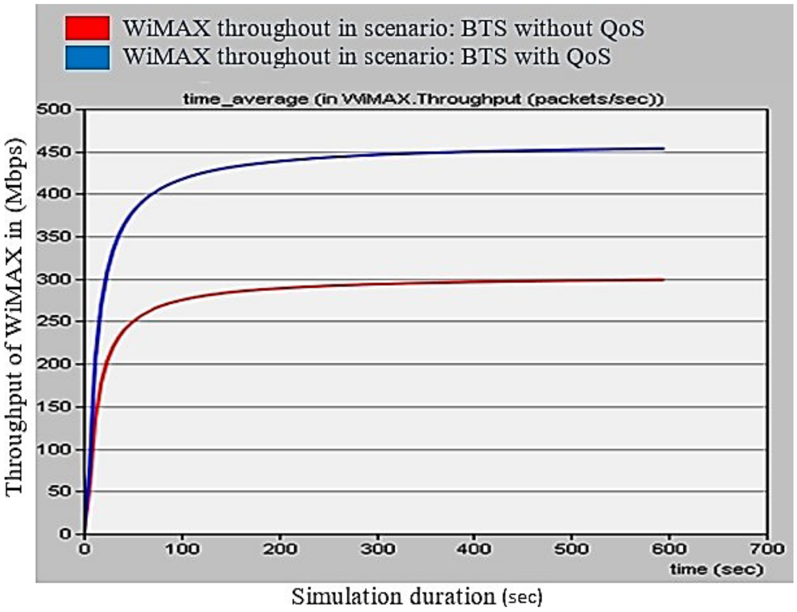


Figure 4.22: WiMAX throughput with and without QoS

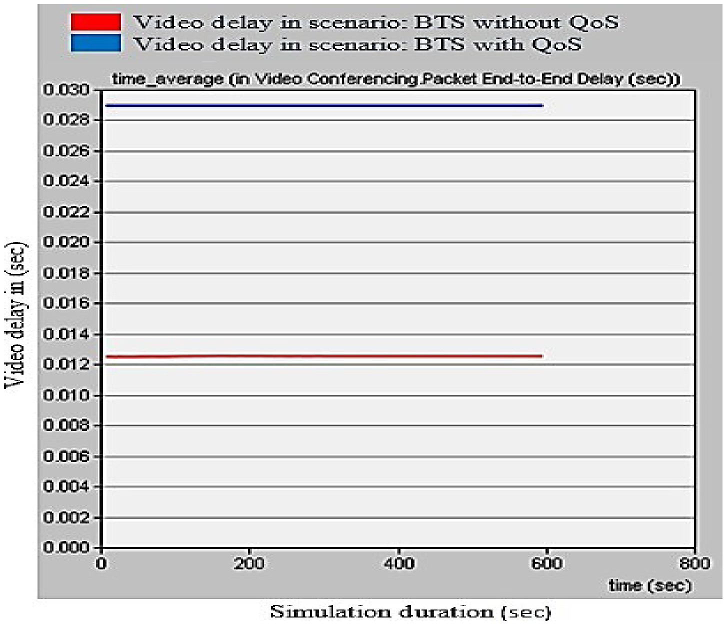


Figure 4.23: Video End-to-End delay in WiMAX

As shown in Figure 4.21 when adding QoS, the delay became negligible: 200ms when using QoS whereas 4 second when no QoS. Also, the throughput has increased 50% (Figure 4.22).

Now, talking about video streaming, the delay has increased (Figure 4.23) and throughput drops down (Figure 4.24), this is an explanation of giving less priority for video since on the other side VoIP is real time app and needs higher priority.

Figure 4.24: Video throughput in WiMAX

4.2.1.3 - Synthesis

Fueled by the motivation of enabling haptic applications such as Haptico-surgical/medical systems at the developing countries, we surveyed the suitability of existing network architectures to convey Tactile Internet multimedia. For that purpose, performance evaluation benchmarks for different type of networks, namely Wi-Fi, WiMAX, and UMTS, were carried out and results show that WiMAX has better performances than Wi- Fi in general. For haptics applications (i.e. UDP+Video streaming), WiMAX proved better performances than UMTS achieving ~1ms Round Trip Delay-RTT which is the most challenging requirement for Tactile Internet applications.

	Distance to Access Point	Sent packets	Received packets	Throughput(Mbps)	Delay(ms)
Wi-Fi	10m	700	700	45	15
	100m	700	550	31	17
	1000m	700	230	18	20
WiMAX	10m	2800	2750	43	4.1
	100m	2800	2200	49	3.7
	1000m	2800	1400	55	3.2

Table 4.2: WiMAX vs. Wi-Fi

		End to End delay (ms)	Jitter (ms)	Throughput (Mbps)
WiMAX	VoIP	8	11.5	55
	Video	12	15	57
	Haptics (UDP)	1	0.3	41
	Haptics +video	7	1.8	53.5
UMTS	VoIP	25	15.5	2.5
	Video	35	26	2.9
	Haptics	15	5.7	4.6
	(UDP)			
	Haptics +video	52	13.4	5.9

Table 4.3: WiMAX vs. UMTS

4.2.2 – Suitability of SDN and MEC to facilitate Digital Twin Communication over LTE-A

The 5G technology is only in its early stages and its cornerstone which makes its standardization and deployment not available anywhere. Further, it has been reported that more than 50 billion devices are already connected to the internet in the year of 2020 [148, 150]. This certainly creates a huge burden on the current network infrastructures such as the 4G as it cannot be able to meet tremendous bandwidth and low latency requirements with such a huge number of devices. Not to forget that the COVID-19 pandemic is not ending soon, hence adding another burden on the internet as most of the daily work is now taking place online. Fired by these motivations, and based on, to the best of the authors' knowledge, integrating SDN/NFV with Mobile Edge Computing (MEC) for future multimedia e.g. (haptic), has not being adequately addressed so far. The main contributions in this next work to come, are as follow:

- Build a framework that takes the advantages of using SDN with MEC, along with existing network mobile infrastructures (like LTE-A), to convey the DT data over existing IP networks.
- Benchmark the suitability of the framework to realize the digital twin architecture in a large-scale over the core of existing mobile networks.

Consequently, instead of using traditional Quality of Service (QoS) approach, such as IntServ and DiffServ, we have incorporated modern networking solutions such as SDN and MEC to achieve that goal. We have shown that the outcome of this study can pave the road to realize what is referred to as tactile bilateral communication channel (i.e. extremely low latency/high reliability, haptic, MR, and audiovisual availability of the internet) even before the deployment of 5G everywhere in the world. The modeling of the DT modalities and their simulations are performed using Riverbed modeler 18.8 [95] based on extracting the traffics from the three Tactile Internet applications that resembles the DT analogy: VoIP, haptic, and high-resolution video streaming.

4.2.2.1 - Methodology

Among the main key research challenges to be addressed for the realization of TI in future networks throughout several applicability domains of TI, is the connectivity issue that requires extremely: (1) low latency of less than 1 ms, (2) high reliability of greater than or equal to 99.999 %,

(3) high data-rate for certain TI applications in the range of 600 Mbps to 1 Tbps and (4) very high backhaul capacity [57, 151].

Many research works have been conducted to tackle the connectivity in the main three domains of TI system. Among them, are the works in [12], and [57], especially for the wireless connectivity in the network domain. In our previous work [113], we investigated the viability of the current IEEE

802.11 (Wi-Fi) and 802.16(WiMAX) standards, for short range, low-latency TI applications. In this work, we focus on the LTE-A radio network connectivity since it is the most wildly used mobile communication universally.

Multiple wireless access architectures, as well as backbone networks, are used in end-to-end (E2E) communications. As a result, maintaining the optimal latency for audio, visual, and haptic data transmission is a critical task. In LTE-A based cellular system, the total latency may be minimized in various network segments, such as the Radio Access Network (RAN), the backhaul, and the core network. According to [154], the total End-to-End (E2E) latency in an LTE-A cellular network is given by equation (4.3):

$$T_{\boldsymbol{E2E}} = 2\left(T_{RAN} + T_{Backaul} + T_{Core} + T_{Transport}\right) \qquad (4.3)$$

where T_{RAN}, $T_{Backhaul}$, T_{Core}, and $T_{Transport}$ are the time it takes for a packet to travel between the user equipment's and the eNodeB base station, (2) the time it takes for the connections between the core network (or EPC- Evolved Packet Core) and the eNodeB, (3) the time it takes to process data at the EPC, and (4) the time it takes to communicate data between the EPC network and the Internet/Cloud respectively. While T_{RAN} depends on coding schemes $T_{Backhaul}$ depends on the medium used, hence our contribution emphasizes, as stated earlier, on the latency minimization techniques to reduce T_{Core}, and $T_{Transport}$. These techniques include innovative methods such as SDN/NFV for T_{Core}, and MEC–enabled cloud/Internet for $T_{Transport}$ since it relies, primarily, on the server's distance from the core network.

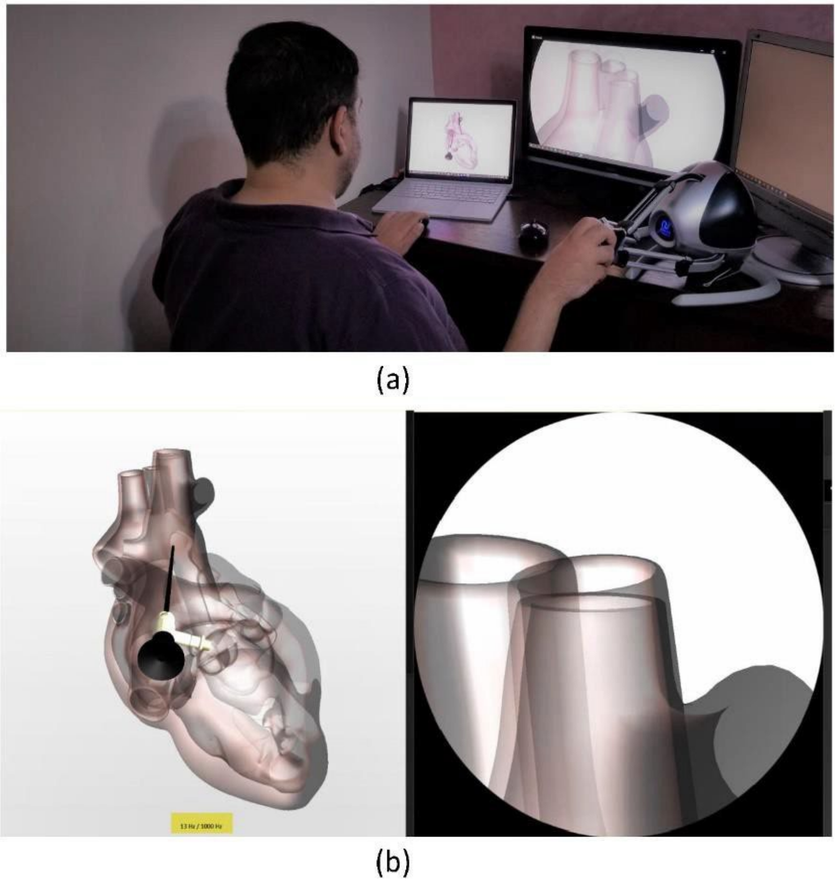


Figure 4.25: (a) An example of Health 4.0 remote surgery using the DT architecture, (b) A proof of concept of Tele- heart-endoscope operation with 1 KHz haptic closed loop sampling rate.

In our work, all computer simulations are carried out by exploiting Riverbed modeler's new

tools and features such as the LTE advanced generation (LTE-A), SDN methodology, and System in The Loop (SITL) capability while running a DT class of application [12] as shown in Figure 4.25. STIL allows the capture, and transfer of simulated data to physical and real network components through the host machine's network adapter. In addition, different models for LTE advanced networks were designed and, using the SITL feature, simulated data were sent to a real *'OpenDaylight' SDN* controller configured on a Linux virtual machine. Therefore, the Network Function Virtualization (NFV), is configured by default when using the SDN controller. Then the network performance regarding of throughput, jitters, and E2E delay were estimated.

4.2.2.2. - LTE-A and the enablers for the New Generation Mobile Networks (NGMN)

To simulate the network performance, several scenarios were designed using Riverbed modeler. The purpose is to investigate particular architectures and technologies that enable the Tactile Internet applications before the massive deployment of the 5G mobile networks. Therefore, in this work, SDN as well other promising technologies such as Mobile Edge Computing (MEC) and Network Function Virtualization (NFV) are first integrated into the core network of LTE-A in different scenarios, then the performance was evaluated and compared. In the next subsections, we provide an overview about the aforementioned technologies

Note that all the coming simulations concerning SDN deployment, include by default the NFV function thanks to the STIL Riverbed Modeler's feature that practically enforce NFV dynamic allocation of resources.

4.2.2.3 - Network Infrastructure: Description of the Network scenarios

Several network scenarios and topologies were designed on Riverbed modeler to evaluate and compare their performance. In addition, Video Conferencing, Streaming and VoIP applications were considered in the study. In the following subsections, details of these scenarios are given.

A. LTE-A Network: Baseline

Figure 4.27 represents the first scenario that corresponds to an LTE-A network only without SDN, NFV or MEC technologies. The scenario comprises the LTE-A core and access networks, and the gateway router. The radio access network (RAN) topology is constructed for several number of cells. Each cell consists of one eNodeB base station along with five randomly distributed devices (User Equipment) that can move on a defined vector-based trajectory. The devices that were used in this topology are described in Table 4.4. Note that this scenario has been simulated with Table

4.5 configuration parameters within Riverbed.

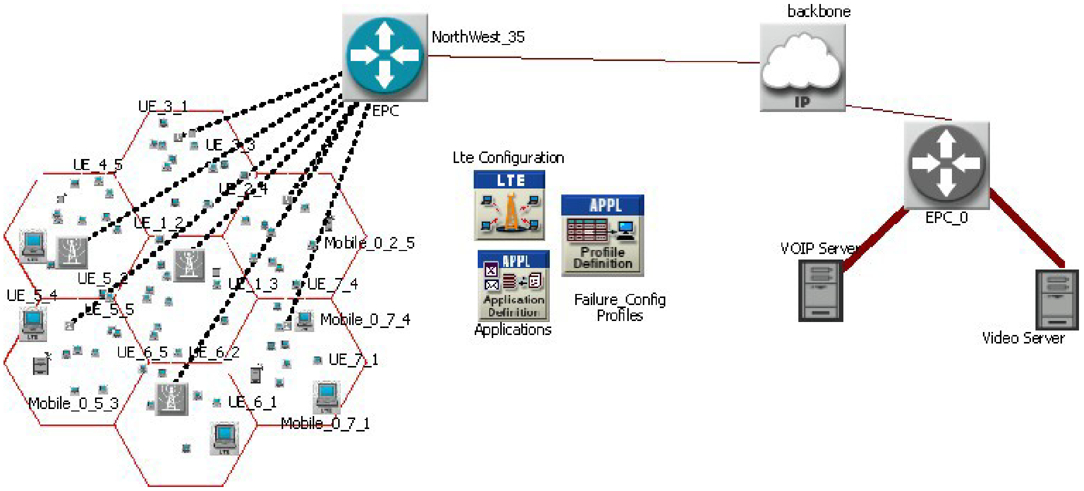


Figure 4.26: LTE-A Baseline Network Scenario

Component	Riverbed Modeler Entity
Base Station	lte_enodeb_4ethernet_4atm_4slip_adv
IP Backhaul	router_slip64_dc
Gateway	lte_access_gw_atm8_ethernet8_slip8_adv
Application Server	ethernet_server
Workstation Application	lte_wkstn_adv
LTE Server	lte_server_adv

Table 4.4: Baseline scenario components

B. LTE-A + MEC Network

The second scenario corresponds to an LTE-A network with MEC integration. Similarly, the RAN consists of seven cells with the major difference of hosting the application servers. This illustrates the idea behind MEC technology wherein computational and storage capabilities are brought closer to the users. The devices that were used in this topology are the same as in the previous scenario with one additional component the Application Server, which is *BBTTCC—TTCCCCssCCCC—BBaass* entity in Riverbed modeler.

Simulation Parameter	Value
Simulation Area	Campus (X=Y=10 km)
Simulation Time	10 minutes
Intermittence Period (Time for the network to get converged)	2 minutes
Number of eNodeB / Cells	7
Cell Radius	1km
Nb of UEs per Cell	5
UE Speed in Movement	10 KMH
Standard	LTE-A Rel.13
Bandwidth	20 MHZ-FDD (Frequency Division Duplex)
Modulation Type	OFDM

Table 4.5: Baseline scenario parameters

C. LTE-A + SDN Network

The third scenario corresponds to an LTE-A network with SDN integration. The proposed model, consists of seven cells with randomly distributed devices that move within the cells. The SDN architecture is composed of Hybrid switches that support both OpenFlow and traditional Ethernet switching technology. They are connected to the Embedded Packet Capture (EPC) router that allows capturing packets that flow to, through or from it. Moreover, the Riverbed System-in- the-loop (SITL) element permits connections between genuine devices, and the simulated network. The SITL module provides packet transmission between real and simulated packets (between data plane and control plane). SITL bridge serves as a foreign device whereby the simulation transfers the packets from the 'OpenDaylight' SDN controller (which is installed on an external machine) to the simulation process on Riverbed. In such a simulation manner, physical hardware and simulation can interact as a unified system. The devices that were used in this topology are denoted in in Table 4.6.

Component	Riverbed Modeler Entity
Base Station	lte_enodeb_4ethernet_4atm_4slip_adv
IP Backhaul	router_slip64_dc
Gateway	lte_access_gw_atm8_ethernet8_slip8_adv
Server	ethernet_server
Workstation Application	lte_wkstn_adv
LTE Server	lte_server_adv
OpenFlow Switch	of_switch_eth16_adv
SDN Controller	OpenDaylight
System in the loop	sitl_virtual_gateway_to_real_world
Modulation Type	OFDM

Table 4.6: SDN scenario parameters

D. LTE-+ MEC + SDN Network

The fourth scenario represents the integration of both MEC and SDN technologies over the LTE-A network, by bringing the clouds closer to the users and by enabling higher flexibility. The SDN Controller has a synopsis of the total network and is in charge of the settlement to be taken, whereas the hardware (switches, routers, etc.) is merely in charge of expediting packets to destination using a set of packet-handling rules. The controller is installed on an external machine connected to the SITL. The devices that were used in this topology are the same as in the previous scenario.

E. LTE-A + MEC + SDN Network for Haptic Audio/Video

To assess the efficiency of the haptic transmission model, we employed our network model described in [12], in which the human-operator and teleoperator workstations are designed to send and receive haptic through the process model with a throughput of about 1000 packets per second using the Riverbed's Task Configuration Utility. Each packet was configured to have a burst size of 74 bytes to represent the haptic (x, y, z) and their correspondent velocity and forces. The fifth scenario is shown in Figure 4.28. It uses the same devices, and the same topology that were used in the previous scenario, except for the operator (haptic client) and the teleoperator closed bidirectional loop back hosted as $h\ apticSRV$.

The devices that were used in this simulation topology are described in Table 4.7.

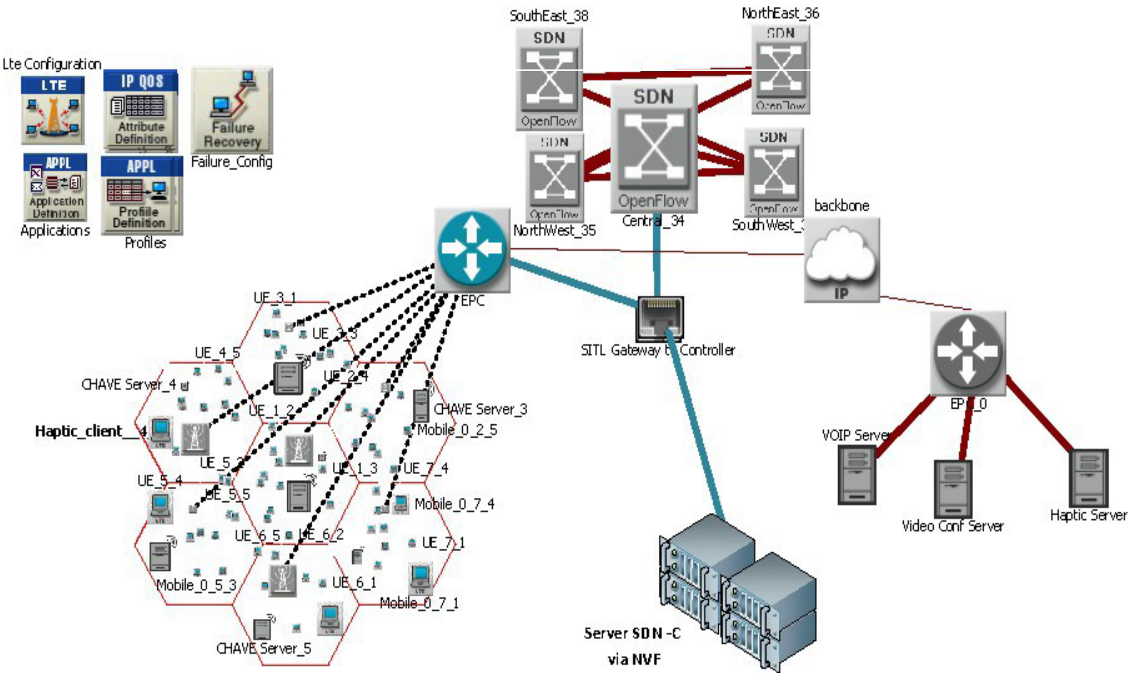


Figure 4.27: Riverbed simulation test-bed scenario: LTE-A Network Scenario with SDN and MEC Integration, for Haptic Audio/Video (HAV)

Component	Riverbed Modeler Entity
Base Station	lte_enodeb_4ethernet_4atm_4slip_adv
IP Backhaul	router_slip64_dc
Gateway	lte_access_gw_atm8_ethernet8_slip8_adv
Number of Cells	7
Cell Radius	1KM

Number of UEs per Cell	5 LTE UE (User Equipment)
UE Speed in Movement	10 KMH
Standard	LTE-A Rel.13
Bandwidth	20 MHZ (FDD)
Modulation type	OFDM
Multimedia Server	ethernet_server
Workstation Application	lte_wkstn_adv
LTE Server	lte_server_adv
OpenFlow Switch	of_switch_eth16_adv
SDN Controller	OpenDaylight
System in the loop	sitl_virtual_gateway_to_real_world

Table 4.7: LTE-A+SDN+MEC scenario parameters

4.2.2.4 - Simulation Results and Analysis

In this section, we show and interpret the most used KPI metrics in Riverbed, which are: E2E delay, throughput, and jitter (delay variation) for each network scenario.

F. Comparison between Baseline LTE-A and LTE-A + MEC

The first and second scenarios were simulated in Riverbed modeler by evaluating the timing performance, in the case of audiovisual streaming, concerning the following metrics: downlink delay and uplink delay. The network simulation time is fixed at 10 minutes (up to 600 sec shown on the x-axis in Figure 4.28) for all cases and it corresponds to a runtime of approximately 1h on a on a commercial pc with Intel core I7 3.0 GHz and 32 GB of ram. Figure 4.28.a shows the downlink delay results in seconds (shown on the y-axis in Figure 4.29) where a peak value of 45ms is achieved in the LTE-A scenario (blue curve) compared to 20ms only in the LTE-A+MEC (red curve) scenario. Integrating MEC into LTE-A has clearly reduced the downlink delay in the network to below 45%. as for the uplink delay, at the beginning of the simulation, the uplink delay in the LTE-A+MEC network was slightly below LTE-A scenario (118ms and 125ms), then it increases to 150 before saturating at a lower value of 130ms. LTE - A network has an almost constant delay during the whole simulation time. The variation of the uplink delay for the LTE-A+MEC scenario is due to the presence of the own edge servers at each cell (besides the main servers) which contributes to the increase of the overall transmission delay at the beginning.

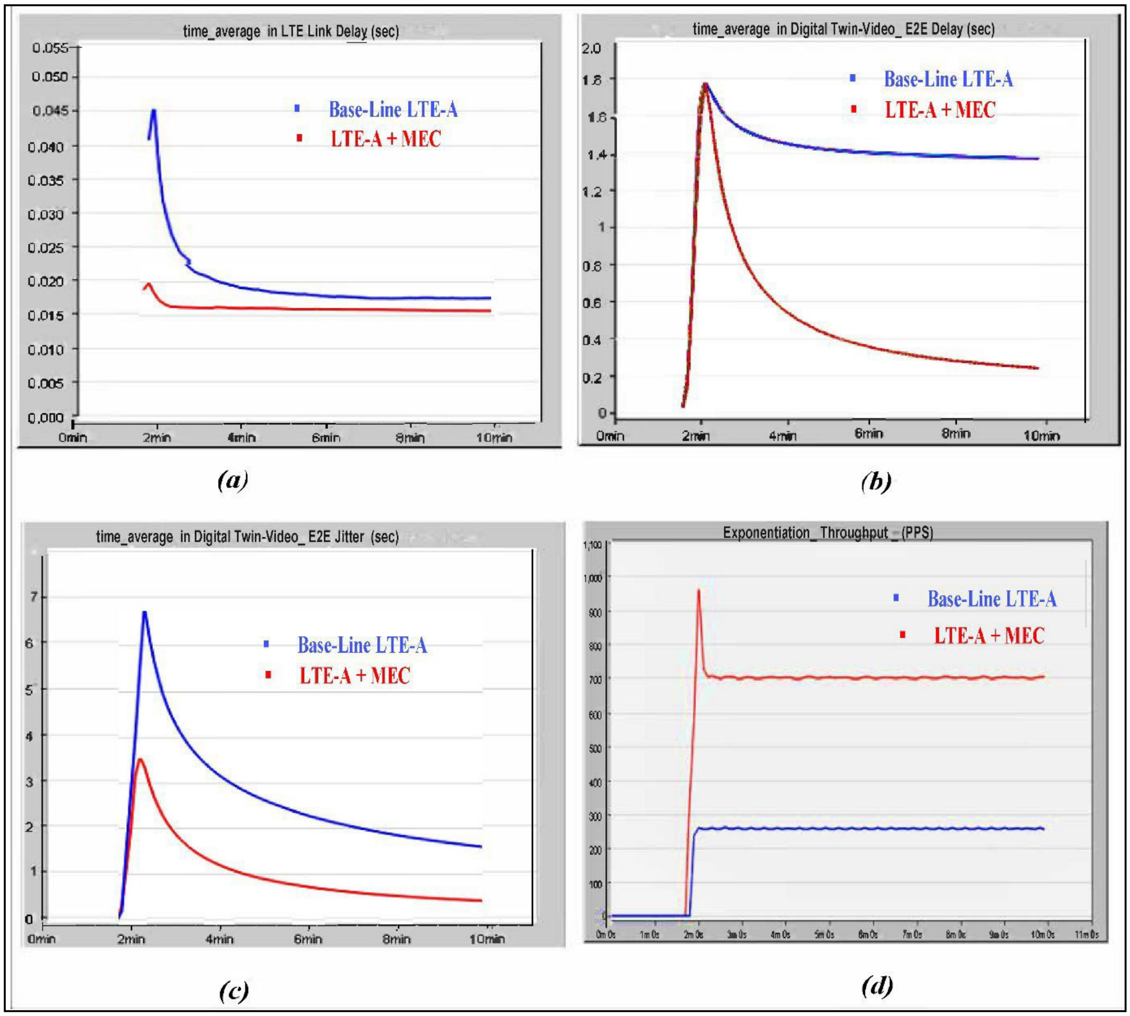


Figure 4.28: Simulation Results: (a) Downlink Delay Results for LTE-A and LTE-A with MEC Integration Scenarios (b) Packet End-to-End Delay Results for LTE-A and LTE-A with MEC Integration Scenarios (Video) (c) Packet Delay Variation Results for LTE-A and LTE-A with MEC Integration Scenarios (d) Throughput for LTE-A and LTE-A with MEC Integration Scenarios

The first and second scenarios were simulated again by evaluating different performance metrics in the case of a Video Conferencing application: Packet End-To-End Delay, Packet Delay Variation. In this context, the Packet End-To-End Delay is the time it takes for a packet to travel from its source to its destination across a network. It represents a different quantity than round-trip time (RTT), the latter takes into account the return path from destination back to source. Figure 4.29 (b) shows that the End-To-End delays in the first and, second scenarios increase at the same rate and reach a peak value of ≈ 1.8 sec (at ≈ 2 minutes from simulation start). Then, in the case of LTE-A+MEC network, it decays exponentially down to ≈ 0.2 sec (the red curve, at 10 minutes from simulation start), while it slowly decreases to 1.4 sec only in the LTE-A network (blue curve). Figure 4.28 (b) shows a clear improvement in the End-To-End delay (7 times lower delay) when integrating MEC in the LTE-A network.

Packet Delay variation is defined as the difference in End-To-End delays between the video packets. Illustrated in Figure 4.28 (c), the maximum variation for the LTE-A+MEC scenario (3.5 s) is only half of the case for LTE-A network only (6.8 s).

The throughput is the successful data rate that is offered to a channel. The unit for the throughput is usually bits per second, but in this work, and since we are simulating video streams over a broadband network (LTE-A), we measure the throughput in packets per second. By comparing the Exponential Moving Average for the throughput of each of the above two first scenarios, it is easy to notice from the Figure 4.28 (d), that the throughput with MEC integration (red curve) is much higher than the sole LTE-A scenario.

According to RFC 4689, jitter is defined as the latency fluctuation between two consecutive packets belonging to the same flow between two systems [134]. This usually occurs because some packets take longer time to travel from one point to another in the system mainly due to network congestion (which is totally random and time-variant), timing drift and route changes. Jitter can be estimated by the following formula:

$$Jitter = \left| (t_{i,r} - t_{i,s}) - (t_{[i-1],r} - t_{[i-1],s}) \right| \qquad (4.4)$$

Where: $t_{[i-1],s}$, $t_{i,s}$, $t_{[i-1],r}$, and $t_{i,r}$ and denote the sending time of packet (i – 1), the sending time of packet i, the time of packet (i – 1), and the time of packet i respectively. In overall, the average or mean value of the jitter over a long period of observation is often the point of interest in terms of the average jitter results for the first and second scenarios, for the DT voice modality, the value in the case of LTE-A+MEC network, is smaller (= 3ms) than the LTE-A case (=15 ms).

G. LTE-A + SDN + MEC and DT Haptic Audiovisual Results

The fifth scenario is simulated in Riverbed modeler by evaluating the timing performance, in the case of a haptic application, in terms of (E2E) delay, jitter, and throughput. The detailed results for this scenario are explored in the following three figures. Given that the haptic model was inspired from [12] at which each packet has a size of 74 bytes (28 byte payload and header + 8 byte UDP header + 20 byte IP header + 18 byte Ethernet header), as such, the maximum throughput shown in Figure 4.29 is 1184 Kbps (i.e.2 times 592 Kbps for each bidirectional haptic (kinesthetic and tactile and stream). Each haptic client was capable to perform the data exchange with the correspondent haptic server in each cell. Consequently, the end-end delay between a haptic master and slave setup was margined to 19 ms as of Figure 4.30.

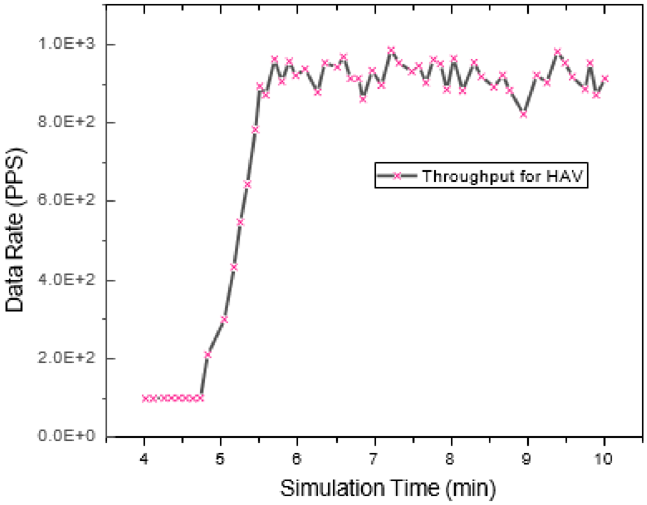


Figure 4.29: Haptic Throughput per Client

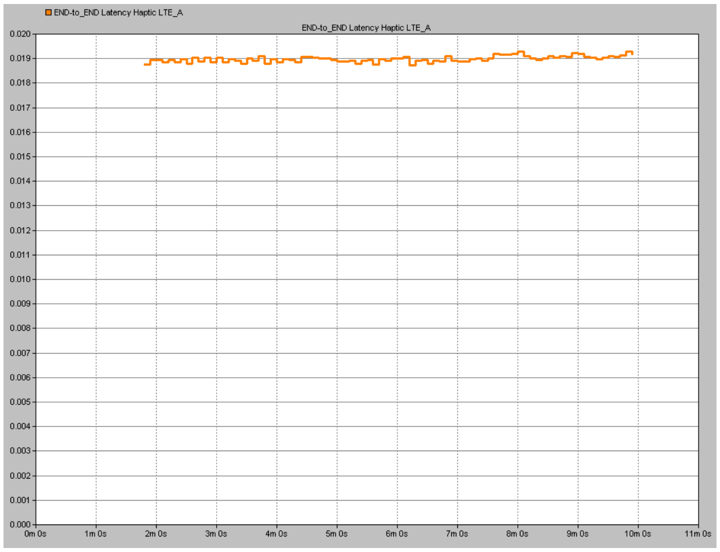
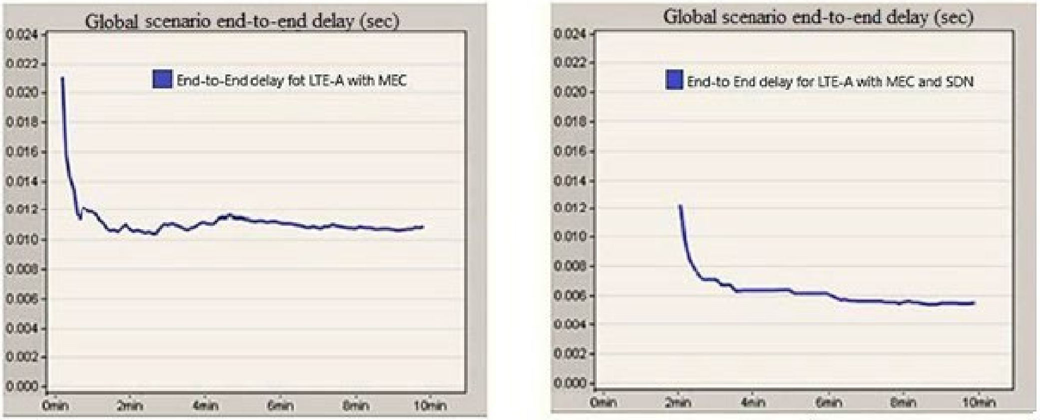


Figure 4.30: Packet End-to-End Delay Results of the LTE-A scenario for haptic

Generally speaking, introducing MEC in the LTE-A network achieves an E2E Delay of only 11ms as shown in Figure 4.31 (a). This performance is way above the required hypothetical specification of 1ms for the Tactile Internet. Therefore, when both SDN and MEC were combined with LTE-A network, the simulated E2E Delay resulted in 4ms, as shown in Figure 4.31 (b). The best scenario possible is clearly the one integrating



(a) (b)

Figure 4.31: Simulation Results for DT modalities (a) Packet End-to-End Delay of LTE-A with MEC Integration Scenario for collaborative haptic AV (b) Packet E2E Delay of LTE-A with MEC and SDN Integration Scenario for collaborative haptic AV

MEC and SDN approaches. We believe that the is the best performance that can be achieved in this simulation topology as the tactile internet demands that the physical transmission must have very small packets to enable a one-way physical layer transmission of 100 µs. However, the duration for the one orthogonal frequency division multiplexing (OFDM) symbol alone is close to 70 µs long under current LTE-A cellular systems. In summary, the results, in the table 4.8, showed that the integration of the MEC and SDN over the LTE-A networks had the best performance in general. For more detail about the result of each scenario, please note that the table below illustrates the QoS parameter of voice, video, and haptic achieved per each scenario.

	End 2 End delay (msec)			Jitter (msec)			Throughput/node (pps)		
	Voice	**Video**	**Haptic**	**Voice**	**Video**	**Haptic**	**Voice**	**Video**	**Haptic**
LTE-A	**120**	**1400**	**19**	**15**	**100**	**60**	**50-60**	**24-60**	**1000**
LTE-A+MEC	**80**	**200**	**11**	**3**	**60**	**5**	**50-60**	**24-60**	**1000**
LTE-A+MEC+SDN	**40**	**100**	**4**	**~0.01**	**10**	**0.01**	**50-60**	**24-60**	**1000**

Table 4.8: Simulations KPI Results Compilation

4.3 - CONCLUSION

The Tactile Internet where haptic is appended to the traditional multimedia communication is one the main technologies used in the development of future network infrastructures such as the fifth generation of mobile networks (5G). When it comes to network resources, haptic is very challenging in terms of latency, jitter, throughput, and packet loss. In the first scenario, with the facility of the Riverbed modeler, we have modeled the networked haptic flow sent by haptic based- ALPHAN application over the Internet. The model was used to evaluate the performance of haptic in a large-scale environment. Based on our experimental study, the provision of the DiffServ priority queuing or custom queuing with LLQ dramatically enhanced the performance of the ALPHAN haptic transmission over a congested IP network.

In the comparative study of the second scenario shown in tables for 4.2 and 4.3, we found that Wi-Fi is adequately suitable at 10 m, but WiMAX is suitable in most of the cases. This reflects the hypothesis we made at the beginning: when we start the study we assume that only WiMAX is suitable for Tactile Internet applications, driven by the need of tele-haptic health and learning systems at the developing countries. Yet, WiMAX has not been deployed, for many reasons. Among others:

1. The deliberate decision of 'incompatible better' instead of 'good enough with a smooth roadmap to better' was, the single biggest reason WiMAX was not successful.
2. The lack of eco-system is a consequence of failure [133].

Consequently, we believed at the first glance, that 5G is needed to perform Tactile Internet applications, although the simulation results of the third scenario demonstrate the suitability of these applications over LTE-A with the boost the New Generation Mobile Networks enablers, SDN, NFV, and MEC.

In the third scenario, we investigated the suitability of current network architectures for delivering future multimedia applications over the Digital Twin and Tactile Internet with the 1 ms latency criteria. Performance assessment benchmarks for various types of networks (i.e. LTE-A, LTE-A+MEC, LTE-A+SDN, LTE- A+MEC+SDN) were carried out for this purpose. To defeat the contests of realizing a Tactile Internet-based system, and to facilitate the 1ms round trip latency come into fruition, SDN, MEC and NFV approaches are what needed to be used to achieve our goal. The deployment of a centralized SDN controller in the center of the mobile network, along with mobile edge computing (or MEC), efficiently improves the network performance and reduces the overheads such as end-2-end delay by managing and establishing a cost-effective and adaptable route between local and remote sides, in this way, the number of intermediate nodes is reduced. We conclude that the proposed structure results in a round trip latency of around very few milliseconds, and this can lead us to the implementation of the Tactile Internet system. One of our contributions in this thesis, is that the before mentioned findings, contradict the hypothesis on current scientific research which presumes that only 5G networks are able to handle DT and TI applications.

Chapter 5 - Conclusion and Future Work

5.1 - Concluding Remarks

In the era of Industry 4 and Digital Twin and the Tactile Internet (TI), it becomes obvious that telecom stakeholders need different networks requirements to provision high quality services with respect to the new standards. The COVID-19 pandemic has increased the internet traffic drastically. Most of the existing networking infrastructures are not capable to effectively host such services. Consequently, new network solutions and tools have to be developed to help solving this issue.

Nowadays, Tactile Internet is in its infancy deployment phase worldwide. For this reason, and because of the growing need of its applications, the feasibility of these applications on the existing and deployed networks infrastructures, especially in the growing countries, is thought to be very hard, even quasi-impossible. Since 5G is not reaching yet its convergence stage (i.e. it is not deployed everywhere) and there is a huge stress on mobile communications given that the world is still facing the COVID-19 Pandemic, and since all the activities are taking place online, here came the idea to design and implement a QoS framework to facilitate the feasibility and the applicability of the DT and the TI systems, where no 5G infrastructure is deployed. This framework will predict the most suitable network type to be deployed for certain given DT/TI applications with certain given KPIs (Key Performance Indicators). Also, this framework is scalable, in such it gives an idea of even the future Next Generation Mobile Networks types (NGMN, if necessary).

DT/TI services and applications are a key type of service in the service domain, allowing high-level business services and applications to add context awareness and experiment with personalization. Yet, given the enormous quantity of DT/TI resources, this is not an easy task. Consequently, a standardization form is necessary for that purpose. The description ontology is a good candidate. It includes descriptions in terms of nonfunctional features (e.g., QoS - and QoE in the future) as well as linkages to domain knowledge, in addition to specifying the functional properties of the applications and services (e.g., input, output, precondition, and impact).

In this thesis, we designed and implemented a state of the art ontology: Service Oriented Development of Haptics Ontology (SODHO) that integrates both sensors and actuators in a unified ontology. We proposed a

QoS KPIs Ontology for the 5G networks (KPION-5G), that relates the future 5G applications to their required network key performance indicators. We designed and implemented an ontology-based framework for Digital Twin and Tactile Internet applications (OFDTI), in which we imported the two previous ontologies in order to infer, along with an integrated Fuzzy Information System, the most suitable network type for a given DT/TI application. We benchmarked existing mobile networks architectures, such as: Wi-Fi, WiMAX, and 3G, to investigate their suitability to carry on the applications of Tactile Internet and Digital Twin applications. And finally, we proposed an architecture at which SDN, NFV (the modern network solutions) are incorporated with MEC to handle DT/TI Communications over LTE-A. The results, in terms of QoS KPIs performance evaluation, present high relevance to our proposed OFDTI Ontology outcomes.

5.2 - FINDINGS

We can resume our findings as follows:

SODHO presented an ontology for haptics to glimpse into the future of Human Computer Interaction. It introduced a Haptics Ontology Platform design that included (sensors and actuators) as well as certain critical concepts.

With Protégé 4.3, we were able to make a relationship between a list of future applications and their requirements by referring to available current network backbones. The developed OFDTI ontology, with the help of an integrated Fuzzy Information System, validated the results of the test cases scenarios simulated in Riverbed Modeler.

From the performance evaluation of the QoS KPIs for Wi-Fi, WiMAX, and 3G wireless systems, and then for LTE-A, we proved that LTE-A boosted by the New Generation Mobile Networks enablers, SDN, NFV, and MEC, is able to handle DT/TI applications. This contradicts the hypothesis on current scientific research which presumes that only 5G networks are able to handle DT and TI applications. And this was powered by the outcomes of the FIS of the OFDTI ontology.

5.3 - FUTURE WORK

As future perspectives, research is directed towards the adding of more inference rules to the description ontologies (i.e. OFDTI, SODHO, and KPION-5G), allowing the deduction of advanced data from basic data. The efficiency will be improved in proportion to the number of inference rules. With this, we will target the model of a unified fully integrated and a lightweight ontology. We can add DT/TI Gateway and Server in SODHO to exploit more outcomes and start building a dataset for multimedia haptics, and multimedia standards.

We recommend the expansion of the Service and Application Test module of OFDTI, in order to model and create the service. Moreover, and as all new generation networks will use the SDN technology along with different new enablers like NFV, and MEC, it is fully recommended to implement the ontology on top of the SDN Controller (SDNC). By targeting these perspectives, and especially with ontology concepts, we believe that, this will increase excessively the new generation services provision on the future networking infrastructures, even better than Artificial Intelligence and Machine Learning propositions.

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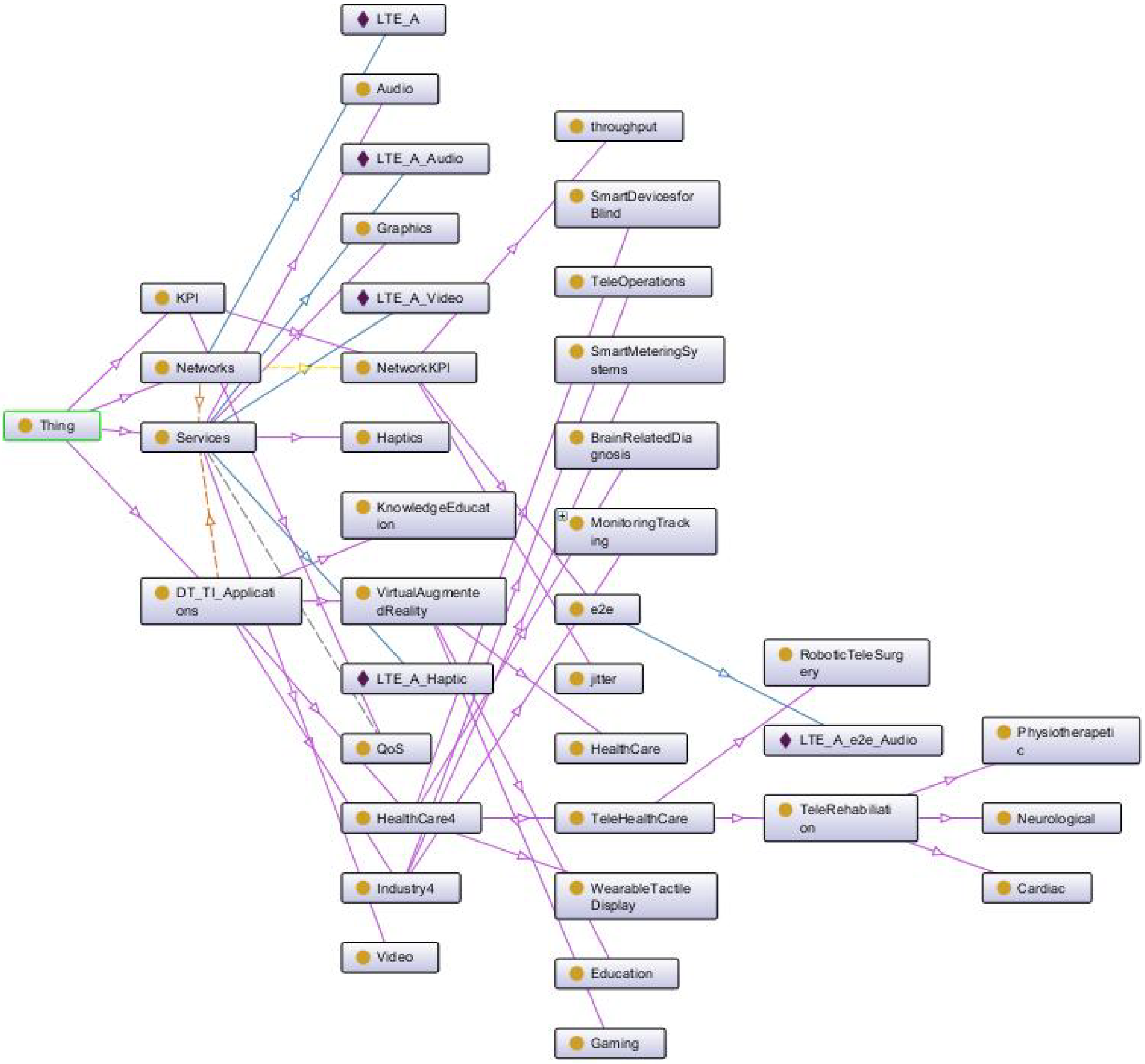
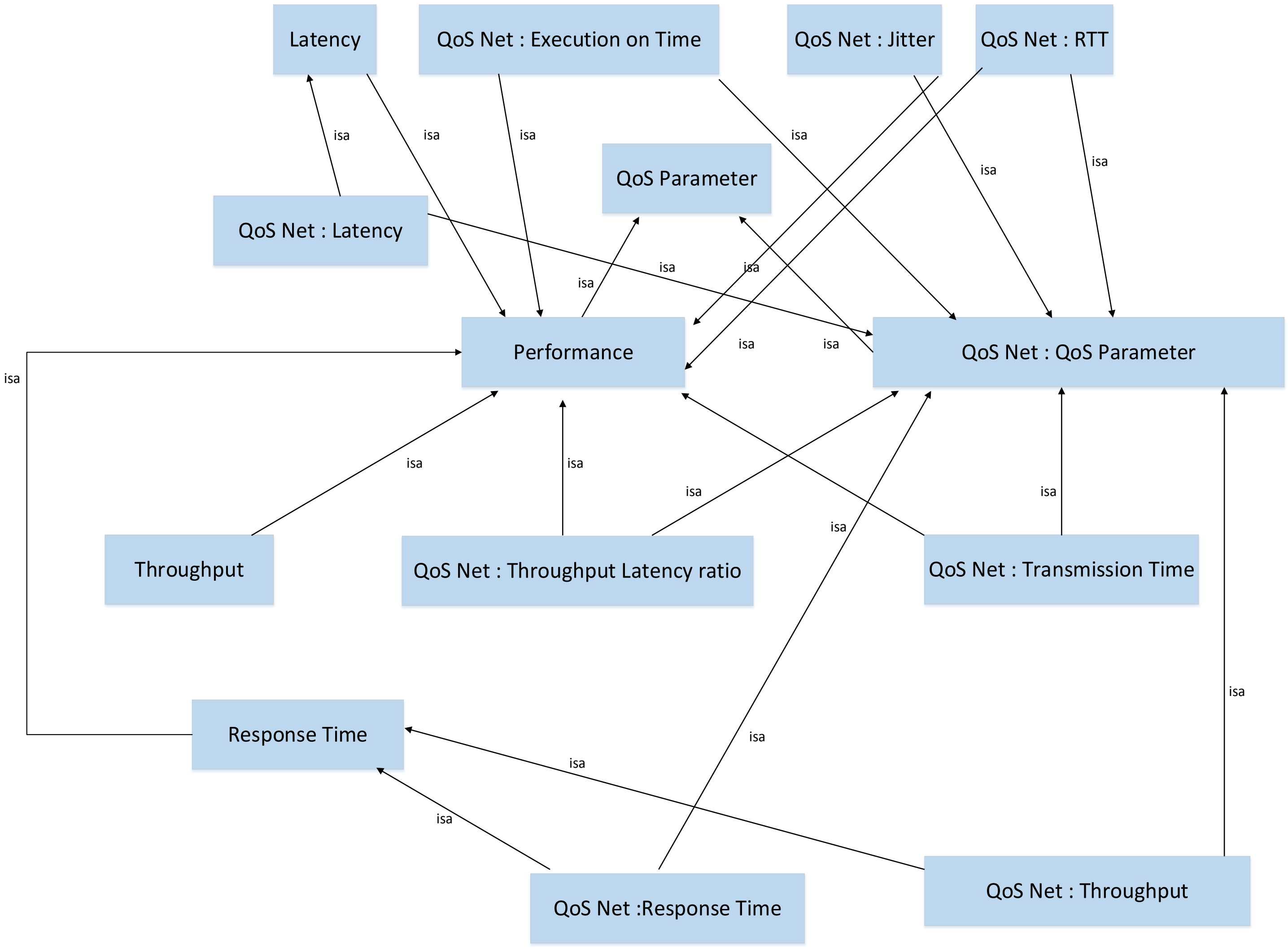
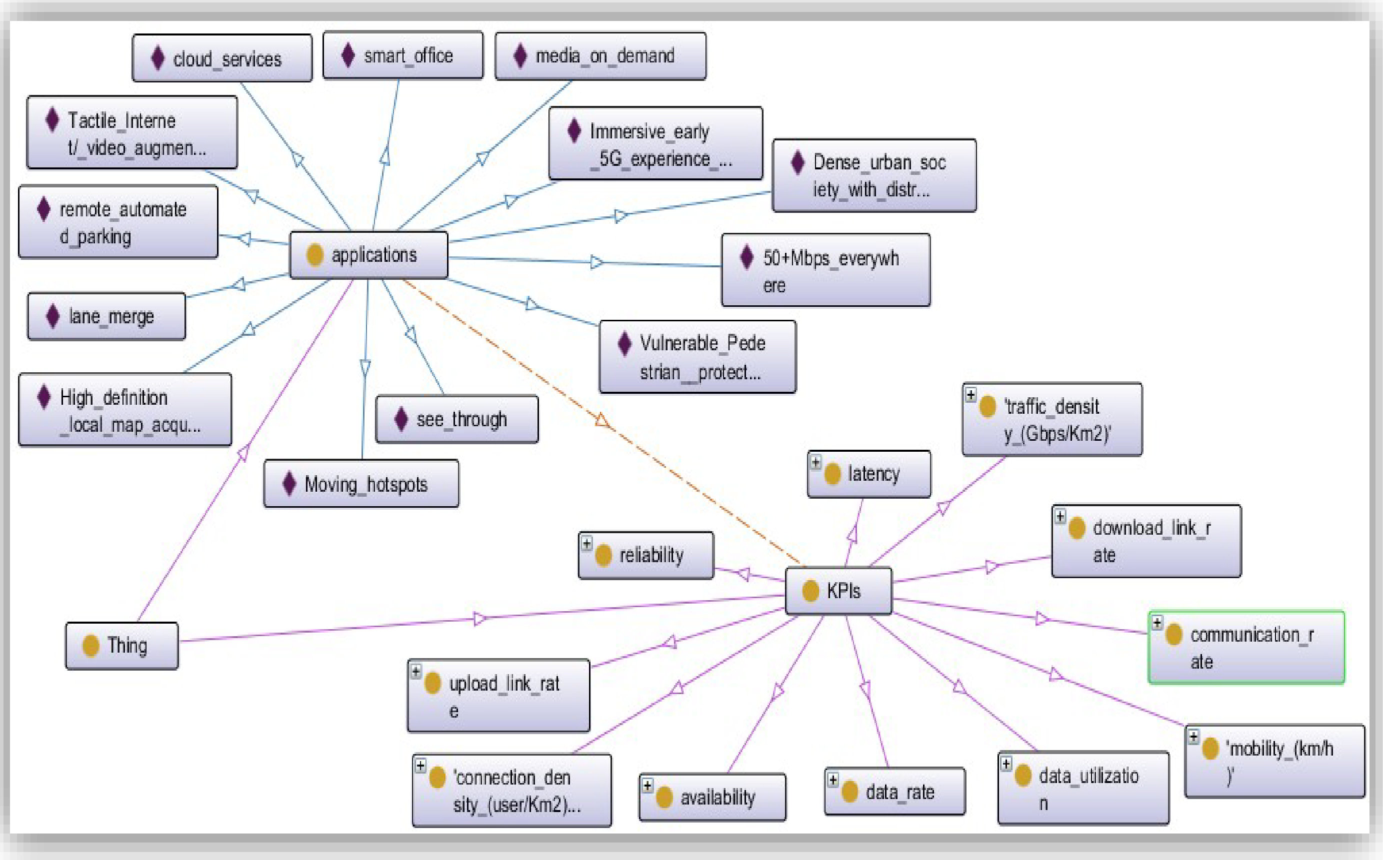
Appendix



Full Ontology



Qos Network Ontology



Ontology which represents 5G apps and related KP