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To my family

Alla mia famiglia

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Contents

Acknowledgements i

List of Figures iv

List of Tables viii

1 Introduction 1

2 Background 5

2.1 QoE modelling . . . 5

2.1.1 Evolution of quality evaluation models . . . 5

2.1.2 QoE models . . . 9

QoE models for the Internet of Things . . . 14

2.2 QoE application scenarios . . . 18

2.2.1 QoE-aware collaboration between OTTs and ISPs . . . 18

2.2.2 QoE-aware Smart Home Energy Management systems . . . 21

3 QoE modelling 24

3.1 Layered QoE model for multimedia services . . . 25

3.2 QoE perception when streaming videos: the impact of system IFs . . . 30

3.2.1 Test video sequences . . . 30

3.2.2 Subjective evaluation procedure . . . 32

3.2.3 Results of the assessment . . . 33

3.2.4 Quality models . . . 35

3.3 QoE perception when streaming videos: the impact of interactivity 36
3.3.1 Test video sequences 37
3.3.2 Subjective evaluation procedure 39
3.3.3 Results of the assessment 40
3.3.4 Quality models 42
3.4 QoE perception when streaming videos: the impact of device switching 43
3.4.1 Test video sequences 44
3.4.2 Subjective evaluation procedure 48
3.4.3 Results of the assessment 49
Device dependency 49
Constant video quality 50
Video quality switching 51
3.5 QoE in the Multimedia Internet of Things 52
3.5.1 Reference IoT architecture 53
3.5.2 The Multimedia Internet of Things 54
3.5.3 QoE layered model for MIoT applications 56
Physical devices layer 57
Network layer 58
Virtualization layer 59
Combination layer 60
Application layer: 60
3.5.4 Analysis of use case: MIoT vehicle application 61
MIoT vehicle application 61
Subjective evaluation procedure 63
Results of the assessment 65
Quality models 67
3.6 Conclusions 69

4 QoE application scenarios 72

4.1 QoE-aware collaboration among OTTs and ISPs 73
4.1.1 Reference architecture for collaboration 74
4.1.2 Collaboration model 76
Pricing modelling 76
Revenue modelling 77
Churn modelling 78
Revenue maximization 79
4.1.3 Simulation 81
QoE models 81
Simulation results 83
4.2 QoE-aware Smart Home Energy Management system 89
4.2.1 System overview and model 90
Energy consumption model for controlled appliances 91
System functional model 92
4.2.2 QoE-driven appliance's usage profile 92
Conducted survey 93
Creation of profiles 97
Selection of the appliance's usage profile 99
4.2.3 Task scheduling model 100
Cost Saving Appliance Scheduling algorithm 102
Renewable Source Power Allocation algorithm 105
4.2.4 Simulation 107
4.3 Conclusions 111

5 Conclusions and future works **113**

Acronyms **116**

Bibliography **120**

List of Figures

2.1 Evolution of quality evaluation models. 9

3.1 Proposed layered QoE model for multimedia services. 29

3.2 Isosurface graph for the video sequences coded at 200 kbps and rated on the Galaxy Tab. MOS values selected for the isosurface computation: 1.7, 2, 2.3, 2.7, 3, 3.3. 33

3.3 Isosurface graph for the video sequences coded at 200 kbps and rated on the iPad 2. MOS values selected for the isosurface computation: 1.7, 2, 2.3, 2.7, 3, 3.2. 34

3.4 Isosurface graph for the video sequences coded at 400 kbps and rated on the Galaxy Tab. MOS values selected for the isosurface computation: 1.7, 2, 2.3, 2.7, 3, 3.3, 3.6. 34

3.5 Isosurface graph for the video sequences coded at 400 kbps and rated on the iPad 2. MOS values selected for the isosurface computation: 1.7, 2, 2.3, 2.7, 3, 3.3, 3.6. 35

3.6 Snapshot of the SV experience. 38

3.7 Snapshot of the VP experience. On the bottom, the user can choose the video to watch from the playlist. 39

3.8 Snapshot of the VP experience showing the subtitles and a text box (in Italian) advertising another video from the same playlist. 39

3.9 MOS results with 95% CI for the SV and VP consumption experiences computed for each of the four video categories, and their average, with (WS) and without (NS) starvation. 41

3.10 Testbed configuration. 47

3.11 MOS values with 95% confidence interval for the 18 TCs. 49

3.12 MOS values as a function of video quality for each viewing mode. 50

3.13 MOS values for videos with constant video quality among the different viewing modes. 51

3.14 MOS values for video quality switching TCs among the different viewing modes. 51

3.15 The considered four-layer model for IoT architectures. 53

3.16 Classification of IoT applications on the basis of the type of information they manage (multimedia or scalar content) and of the type of recipient (person or system oriented). 55

3.17 Multimedia IoT (MIoT) scenarios: (**a**) multimedia as IoT input and output: IoT application that presents in a multimedia way information acquired by multimedia objects; (**b**) multimedia as IoT input: IoT application that uses information acquired by multimedia objects; (**c**) multimedia as IoT output: IoT application that presents in a multimedia way information acquired by IoT objects (scalar content). 57

3.18 The proposed layered QoE management framework. 58

3.19 Framework of the MIoT vehicle application for remote tutoring for driving school lessons. 62

3.20 Screenshot of the web MIoT application with analog speed and rpm indicators. 63

3.21 Screenshot of the web MIoT application with digital speed and rpm indicators. 63

3.22 MOS results with the 95% confidence interval comparing low and high video qualities being equal in the other conditions. 66

3.23 MOS results with the 95% confidence interval comparing analog and digital presentation of vehicle parameters being equal in the other conditions. 66

4.1 Reference architecture for the collaboration between ISP and OTTs. 75

4.2 User churn function for different values of $QoE^m_{i,j}$ and z. Continuous curves refer to $QoE^m_{i,1} = 2.5$ whereas dotted curves refer to $QoE^m_{i,2} = 4$. 80

4.3 Number of starting users for standard (ST) and premium (PR) classes of service as a function of the prices $P_{i,1}$ and $P_{i,2}$. 85

4.4 Revenue obtained with the two approaches by the two OTTs in the first 2 years varying $P_{i,1}$ from 0.1 to 0.5 and with $P_{i,2} = 0.6$. 86

4.5 Revenue obtained with the two approaches by the two OTTs in the first 2 years varying $P_{i,1}$ from 0.1 to 0.5 and with $P_{i,2} = 0.8$. 87

4.6 Revenue obtained with the two approaches by the two OTTs in the first 2 years varying $P_{i,1}$ from 0.1 to 0.5 and with $P_{i,2} = 1.0$. 88

4.7 QoE provided by the video and VoIP applications for the NC and JV approaches, in terms of the MOS with 95% confidence interval. 89

4.8 Reference scenario 91

4.9 Part of the survey page of the washing machine in which the users can select the preferred starting times for working days. 95

4.10 Pop up page of the survey in which the users can select their saving preferences for switching controlled appliances. 96

4.11 Usage profiles computed for each appliance for working days. For each appliance, also the silhouette value obtained by selecting that number of usage profiles and the percentage of users belonging to each usage profile are indicated. 98

4.12 Usage profiles computed for each appliance for days off. For each appliance, also the silhouette value obtained by selecting that number of usage profiles and the percentage of users belonging to each usage profile are indicated. . . . 99

4.13 Flow chart of the proposed SHEM system. 101

4.14 Daily power production for photovoltaic (PV) and wind turbine systems [1]. . . 109

4.15 Energy cost savings using the proposed QoE-aware SHEM system and the QoE-unaware SHEM system in [2], in the case where RES are not installed (wo RES) and in the case where RES are installed (w RES). 110

4.16 Annoyance rate with the proposed QoE-aware SHEM system, compared with the QoE-unaware SHEM system in [2]. 110

List of Tables

2.1 Comparison between state of the art works proposing QoE models. 11

3.1 Values of the encoding (bitrate) and transmission parameters used to generate the distorted video sequences. 31

3.2 Values of the encoding parameters. 31

3.3 Values of the coefficients for both the linear and the nonlinear regression in Eqs. (3.1) and (3.2). 36

3.4 Pearson correlation values computed between the proposed quality models and the MOS results. 36

3.5 Video and audio encoding parameters for the selected video sequences. 38

3.6 Pearson correlation values computed between the MOS_V and the QoE models defined in Eqs. (3.5)-(3.8). 43

3.7 Video and audio encoding parameters for the selected video sequences. 45

3.8 Test Conditions (TCs). 46

3.9 Test Conditions (TC). 64

3.10 Values of the coefficients for the linear regression in Eqs. (3.13)–(3.15). 68

3.11 Values of the coefficients for the nonlinear regression in Eqs. (3.16)–(3.18). . . 68

3.12 Values of the Pearson correlation between the MOS_V values and the quality models defined in Eqs. (3.19)–(3.22) with regard to the digital data presentation. 69

3.13 Values of the Pearson correlation between the MOS_V values and the quality models defined in Eqs. (3.19)–(3.22) with regard to the analog data presentation. 69

4.1 Key parameters about appliance i for each Group of appliances. 93

4.2 Characteristic parameters of appliances [1, 3, 4]. 108

4.3 ENEL pricing. 109

Chapter 1

Introduction

Internet traffic has evolved over the past decade from web traffic to multimedia traffic due to the widespread use of powerful mobile devices (e.g., smartphones and tablets) and significant advancement in multimedia services over the Internet (e.g., HTTP multimedia streaming, videoconferencing, VoIP, mobile gaming, IPTV). Recent studies on trends in Internet traffic have predicted that more than 75% of the world's mobile data traffic will be multimedia by 2021 [5] and Over The Top (OTT) services such as Facebook, YouTube, Skype, Amazon, Netflix, are the major responsible of the distribution of multimedia content over the Internet. Such a drastic increase in the use of multimedia services has introduced critical issues for Internet Service Providers (ISPs), which have to upgrade their networks to provide the tremendous network resources requested as well as to assure the required level of quality to the users. Indeed, in this era of strong competition in this domain, both network and application providers have to consider another differentiator than just price, i.e., the quality of their service. Providers must take into account users' quality requirements to avoid the risk of user churn, which may result into decrease of market share and reputation.

For these reasons, in the last years the concept of Quality of Experience (QoE) has become very important to evaluate the quality of information and communication technology (ICT) systems and services, because it considers the quality from a perceiving person's point-of-view. QoE evaluation overtakes the limits of Quality of Service (QoS) measurements, which are system-centered and do not consider application related parameters if not other factors, such as human and context factors [6]. These would allow for obtaining measures closer to the QoE, which reflects the quality as perceived by the user. However, QoE evaluation is not straightforward and requires the organization of subjective quality assessments in which sample people are asked to rate the quality of an application or service. Though, these are time consuming and unsuitable for real-time applications (e.g., quality monitoring and management). Thus, objective QoE models are preferred, which aim to define a mathematical relationship between different measurable QoE influence factors (IFs) and quantifiable QoE dimensions for a given service scenario. Such models serve the purpose of making QoE estimations, given a set of conditions, corresponding as closely as possible to the QoE as perceived by end users [7]. Many QoE models have been proposed in the literature, which consider several IFs and follow different modelling approaches making it difficult to compare the proposed methods and to combine their results in the effort of achieving better performance. This has brought to the issue of modelling un-interoperability, i.e., the unfeasibility of integrating the results of different modelling activities to broaden the range of scenarios where the integrated model can be applied. QoE modelling is the focus of the first part of this thesis: a layered QoE modelling approach has been investigated to solve the issue of modelling un-interoperability; subjective assessments have been conducted to define objective QoE models for video streaming service and validate the proposed layered model; and a first approach on QoE modelling for Internet of Things (IoT) applications has been proposed.

In the last years, various application scenarios have emerged, for which QoE has been considered to drive QoE-aware management of system resources: in vehicular networking, multimedia streaming services have rise to the challenge of supporting high QoE for interactive Video on Demand (VoD) mobile service [8, 9]; novel studies are being conducted regarding how mulsemedia (MULtiple-SEnsorial media) content affects QoE as perceived by the users subjected to multisensorial stimuli (e.g., haptic, scent, airflow) [10, 11]; 5G networks are being designed to be user-centric and provide high QoE with a network adaptable to dynamic user, service, and network/UE resource availability [12]; smart cities challenges regard not only to ensure high performance with respect to the node mobility and the energy consumption but also to guarantee high levels of QoE perceived by the end-user [13]. These are just some examples of new application scenarios which are attracting the interest of researchers for the definition of QoE models to be used in novel QoE-aware management systems.

The second part of this thesis focuses on two specific QoE application scenarios. The former regards the investigation of a QoE-aware collaboration approach between ISPs and OTTs for efficient multimedia service delivery. It is a matter of fact that the proper management of QoE brings to direct economic advantages: if a customer does not receive adequate QoE, it is more likely to become a churner, i.e., a customer leaving a service. Then, the QoE may be the key to solve the user churn problem common to ISPs and OTTs. The latter concerns the definition of a QoE-aware Smart Home Energy Management (SHEM) system for controllable appliances, which aims to reduce the electricity costs while preserving the QoE perceived by the users. Due to the strong correlation between the QoE and user's preferences and expectations, the QoE may be measured for profiling the users by investigating their preferences with regard to the utilization of the appliances in a smart home and their annoyance suffered when the operations of appliances are changed with respect to their ideal preferences. The objective is to group the users providing similar responses into common profiles, which can be used to drive the SHEM system so that a trade-off between energy expenses and annoyance perceived is achieved.

The remainder of this thesis is structured as follows.

In Chapter 2, the state of the art is presented. Specifically, past studies related to QoE modelling are discussed and a background on two different QoE application scenarios is provided: QoE-aware collaboration approaches between ISPs and OTTs; and QoE-aware SHEM systems.

Chapter 3 is focused on QoE modelling. First, a layered modelling approach for evaluating the QoE of multimedia services is proposed to address the problem of modelling un-interoperability. In the proposed model, each layer is devoted to a specific QoE domain (set of IFs), so that the overall quality can be computed as a combination of all domains. To investigate the applicability of the proposed layered model, a video streaming scenario is considered: the influence of system and interactivity IFs on the QoE perceived by the users when streaming video sequences on tablet devices are evaluated and combined for the estimation of the overall QoE. Additionally, the influence of device switching on the QoE perceived by users watching video contents is investigated. The aim is to demonstrate that the QoE is not only related to the video consumption on the single device, but it takes into consideration the overall experience of watching the whole video by switching between different devices. Finally, a first approach on QoE modelling for the IoT is presented. Firstly, a reference IoT architecture is analyzed to provide guidelines on which IFs should be considered and measured for the evaluation and management of the QoE of IoT applications. Secondly, the concept of Multimedia IoT (MIoT) is introduced in order to focus on the applications in which people are involved as the end-users of the multimedia content provided by the MIoT applications. Thirdly, a layered QoE management framework is proposed, which aims at evaluating and controlling the contributions of each IF to estimate the overall QoE in MIoT applications.

Chapter 4 focuses on two specific QoE application scenarios. The former regards the investigation of a QoE-aware collaboration approach between ISPs and OTTs for efficient multimedia service delivery. Indeed, the provision of QoE is considered as the common objective for OTTs and ISPs because delivering good QoE helps to decrease the user churn and consequently to increase the revenue. However, individually, the ISP and the OTT have limited resources for QoE provision: the ISP has the control of the network but it is not able to measure the QoE perceived by the users; on the other hand, the OTT is aware of the QoE perceived by the users but does not have any control on the network. Therefore, a QoE-aware collaboration approach between ISP and OTT has been proposed, which is driven by the maximization of the revenue based on different factors, such as the user churn, pricing and marketing actions. The latter concerns the definition of a QoE-aware SHEM system for controllable appliances, which aims to reduce the electricity costs while preserving the QoE perceived by the users. The QoE is used as a priori measure of user's satisfaction for profile characterization of the involved users appliances of a SHEM system. A survey has been conducted to collect users' preferences, which have been clustered in different profiles: the QoE is considered as the degree of annoyance perceived when the starting time or the set temperature of appliances in a Smart Home is modified with respect to users' preferences. The SHEM system runs a task scheduling model, which relies on two algorithms: the QoE-aware Cost Saving Appliance Scheduling (Q-CSAS) algorithm that is aimed at scheduling controlled loads based on users profile preferences and electricity prices; and the QoE-aware Renewable Source Power Allocation (Q-RSPA) algorithm that modifies the working schedule of appliances whenever a surplus of energy has been made available by renewable sources.

Finally, Chapter 5 concludes the thesis. The contributions of this thesis to the research on QoE modelling and on the two considered QoE application scenarios are highlighted, together with future research objectives.

Chapter 2

Background

In this Chapter, the state of the art is presented. Section 2.1 focuses on the state of the art regarding Quality of Experience (QoE) modelling. First, the evolution of quality evaluation models is analyzed. Then, several QoE models proposed in the recent past are compared and discussed, with a particular focus on QoE models for video streaming services and Internet of Things (IoT). In Section 2.2, a background on emerging QoE application scenarios is provided. Then, related works are discussed regarding two specific scenarios: QoE-aware collaboration approaches between Internet Service Providers (ISPs) and Over The Top (OTT) services; and QoE-aware Smart Home Energy Management (SHEM) systems.

2.1 QoE modelling

The state of the art regarding QoE modelling is presented in this section. Specifically, Section 2.1.1 analyzes the evolution of quality evaluation models, from Quality of Service (QoS) measurements to QoE modelling, whereas Section 2.1.2 compares and discusses several QoE models proposed in the literature, with a particular focus on QoE models for video streaming services and IoT.

2.1.1 Evolution of quality evaluation models

QoS evaluation has been widely studied as a framework for guaranteeing service performance to end-users. A definition of the QoS was provided by the International Telecommunication Union (ITU) in the 2008 ITU-T Recommendation E.800 [14]:

Quality of Service (QoS): Totality of characteristics of a telecommunications service that bear on its ability to satisfy stated and implied needs of the user of the service.

QoS is technology-centric and typically provides service performance via Key Performance

Indicators (KPIs), such as delay, packet loss, jitter, and bandwidth. Another common QoS application is QoS monitoring for detecting Service Level Agreement (SLA) violations. SLA is a service contract defining the user's QoS requirements, and QoS measurements are made to prove the real behaviour of the system. The main advantage of the QoS concept is that it is easily measurable and quantifiable. Consequently, engineers can check whether the network is performing well, clear agreements can be defined at the network and system interfaces, and objective troubleshooting can be conducted with clear targets. On the other hand, the end-users often do not care about how KPIs influence service quality, rather they are concerned about the way they perceive the selected service, whose success is, in turn, determined by the number of satisfied users. Therefore, a first definition of quality as perceived by users is provided again in the ITU-T Recommendation E.800 [14]:

QoS experienced/perceived by customer/user (QoSE): A statement expressing the level of quality that customers/users believe they have experienced.

> **NOTE 1:** The level of QoS experienced and/or perceived by the customer/user may be expressed by an opinion rating.
>
> **NOTE 2:** QoSE has two main man components: quantitative and qualitative. The quantitative component can be influenced by the complete end-to-end system effects (network infrastructure).
>
> **NOTE 3:** The qualitative component can be influenced by user expectations, ambient conditions, psychological factors, application context, etc.
>
> **NOTE 4:** QoSE may also be considered as QoSD (QoS delivered/achieved by service provider) received and interpreted by a user with the pertinent qualitative factors influencing his/her perception of the service.

Thus, researchers started to study the impact of QoS parameters on the users' quality perception. Indeed, most of the proposed models aim at mapping QoS to QoE; they often differ from each other in terms of the selected parameters and how these are combined together. Quite reasonably, QoS degradation typically implies a decreased QoE, which makes it interesting to investigate the relationship between QoE and QoS. For instance, in [15] an exponential interdependency of QoE and QoS is studied, called IQX hypothesis. The feasibility of the proposed exponential relationship is demonstrated through a couple of case studies, addressing among others voice quality as a function of loss, jitter, and reordering; user ratings as a function of response times; and cancellation rates of web surfers as a function of access link bandwidth. On the other hand, in [16] a logarithmic relationship between QoS and QoE is investigated. Specifically, the Weber-Fechner Law (WFL) states that in many cases the percipience of the human sensory system depends logarithmically on the magnitude of the physical stimulus. Therefore, the authors extended the WFL to the assessment of QoE in communication systems and investigated some cases of logarithmic dependencies between QoS and QoE, and specifically the dependency of user-perceived speech quality from technical parameters like bitrate or packet losses and the impact of available bandwidth in the context of downloads.

QoS-QoE relationship models can be defined as models which derive the relationship between QoS and QoE scores, based on the comparison between the reference and the received content. The term *reference content* refers to the original undistorted multimedia content, while *received content* refers to the potentially distorted multimedia content received by end-user after the whole transmission process. A useful classification of QoS-QoE relationship models is proposed in [17], which groups the methods into media-layer, parametric packet-layer, bitstream layer, and parametric planning models. The media-layer models measure the expected quality on the basis of media signals, while the parametric packet-layer and the bitstream layer models are based on packet header and bitstream information, respectively. Requiring a priori information about the system under testing, parametric planning models are able to consider the whole transmission system, from the source to the users. With respect to the other models, planning models allow for some parameters, such as media content, interactivity and context of use, which are closer to the users perception and are not strictly correlated to QoS measures. For this reason, parametric planning models cannot be considered as pure QoS-QoE relationship models.

QoS-QoE relationship models just provide a correlation between changes in QoS parameters and the corresponding changes in the users' perceived quality. These methods are limited to the estimation of multimedia quality on the basis of QoS parameters, that is, they basically interpret QoS measurements into perceived user experiences. Furthermore, most QoS-QoE relationship models are developed for voice and video services, lacking of universal applicability in the case of other services. Thus, researchers started to consider the quality from a perceiving person's point-of-view bringing to the concept of QoE, whose first definition is provided again by the ITU in the ITU-T Recommendation P.10/G.100 [18], as follows:

> **Quality of Experience (QoE):** The overall acceptability of an application or service, as perceived subjectively by the end-user.
>
> > **NOTE 1:** Quality of Experience includes the complete end-to-end system effects (client, terminal, network, services infrastructure, etc.).

NOTE 2: Overall acceptability may be influenced by user expectations and context.

Two years later, in the 2010, a second definition of the QoE was provided by the European Telecommunications Standards Institute (ETSI) in the Technical Report 102 643 [19]:

Quality of Experience: Measure of user performance based on both objective and subjective psychological measures of using an ICT service or product.

NOTE 1: It takes into account technical parameters (e.g. QoS) and usage context variables (e.g. communication task) and measures both the process and outcomes of communication (e.g. user effectiveness, efficiency, satisfaction and enjoyment).

NOTE 2: The appropriate psychological measures will be dependent on the communication context. Objective psychological measures do not rely on the opinion of the user (e.g. task completion time measured in seconds, task accuracy measured in number of errors). Subjective psychological measures are based on the opinion of the user (e.g. perceived quality of medium, satisfaction with a service).

Additionally, due to the growing important of the QoE, an European Network on Quality of Experience in Multimedia Systems and Services, called Qualinet, was established in 2011 [20]. Qualinet was composed of many European researchers with the objective to create a network for multidisciplinary QoE research in Europe. In the 2013, Qualinet published a white paper in which a new definition of QoE is provided [6]:

Quality of Experience (QoE): Is the degree of delight or annoyance of the user of an application or service. It results from the fulfilment of his or her expectations with respect to the utility and/or enjoyment of the application or service in the light of the user's personality and current state.

Additionally, the definition of influence factor (IF) is provided:

Influence Factor: Any characteristic of a user, system, service, application, or context whose actual state or setting may have influence on the Quality of Experience for the user.

From these definitions, it is evident that the QoE aims to represent the quality as perceived by the users of a service by considering both objective and subjective factors which may influence

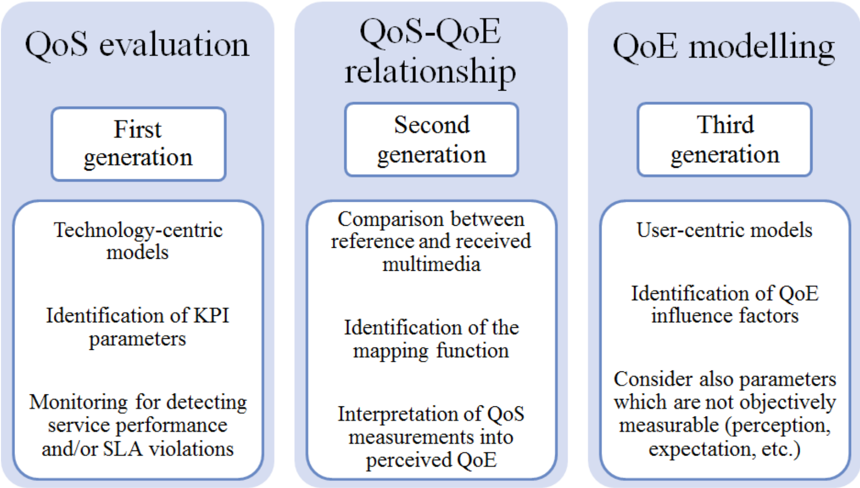

Figure 2.1: Evolution of quality evaluation models.

the perceived quality. There is a complete inversion from traditional QoS technology-centric models to QoE user-centric models. Additional factors as the usage context, business models, interactivity, and also environmental, psychological, and sociological factors, including user expectations and experience, started to be taken into account.

As a consequence, more recent works aim at studying the whole communication system and at investigating, defining and classifying additional factors which influence the end-to-end QoE. Thus, the objective of QoE modelling is to define a relationship between QoE IFs and the end-user perceived QoE. A common factor for QoE models is the evaluation of the QoE as a multi-dimensional value. QoE models are still based on QoS-QoE mapping functions in relation to measurable parameters. However, they differ from QoS-QoE relationship models in that several other IFs, such as human and context IFs, are taken into account, which are not measurable through QoS metrics. These would allow for obtaining measures closer to the QoE, which reflects the quality as perceived by the user. Figure 2.1 summarizes the evolution of quality evaluation models.

2.1.2 QoE models

QoE modelling aims to provide a relationship between different measurable QoE influence factors (IFs) and quantifiable QoE dimensions for a given service scenario [7]. Since the evaluation of the QoE through subjective quality assessments is costly and unsuitable for real-time applications (e.g., quality monitoring), QoE modelling has become very important for QoE-aware management of networks and services. Indeed, QoE models serve the purpose of making QoE estimations, given a set of conditions and IFs, corresponding as closely as possible to the QoE as perceived by end users.

By extending the analysis introduced in [21], Table 2.1 provides a comparison between several QoE models proposed in the recent past. The classification has been conducted in terms of the considered QoE IFs, the type of proposed model, and the application field for which the models have been built. The considered IFs are related to different domains: human, system, context, business and interactivity. Human factors are further classified into human roles, human demographic attributes, subjective QoE factors and objective QoE factors. Note that even if the same factor is included in different works, it does not mean that the same definition is adopted. It often happens that several works do not follow the same classification, as IFs are classified into domains (also called categories/spaces/layers/dimensions) which have not a uniform definition. As an example, in some papers the business factor is considered as one of the main domains [21–23], while in others the business/economic factors are considered as attributes of other domains (generally of the context domain [6, 24–27]).

From Table 2.1, it can be observed that there are two types of proposed QoE model: framework and layered model. While for the framework type the relationships among different IFs for QoE evaluation do not follow general rules but each study proposes a different view, for the layered approach the relationships among IFs follow the rule of layered models, i.e., the quality provided by the IFs considered in the higher layers are in turn evaluated utilizing the quality provided by the IFs considered in the previous layers. The applications for which the QoE models have been defined are various, ranging from Communication and Networking infrastructures to Multimedia services, Human-Machine (H-M) interaction and Next Generation Networks (NGN). With regard to the considered QoE IFs, system and human IFs have been considered by all investigated works; this was expected, since system (QoS) parameters are fundamental in measuring the service performance, which is subjectively evaluated by the end-users. A few works have considered all human IFs, while most have considered only a few of them. Since QoE models represent user perception, all investigated works have considered human subjective QoE factors. Context and business IFs have been widely considered except by few works: the two oldest QoE models [22, 28] and a recent layered model [25] do not include context IFs, while business IFs have not been considered by [29] and [31]. Finally, interactivity IFs have been included in a few works: only three out of eleven have taken into account the influence of interactivity features between user and systems/services in QoE modelling.

The QoE models analyzed in Table 2.1 are theoretical models that provide an overview of all the IFs that should be considered for the QoE evaluation in a specific application field. However, these models are not practical and cannot be used for QoE monitoring and management applications. Indeed, besides understanding which QoE IFs should be considered for QoE evaluation of a specific service, there is the need to measure the impact of each IF on the overall QoE. Therefore, a mathematical relationship must be found between IFs and the QoE. This is

Table 2.1: Comparison between state of the art works proposing QoE models.

Ref.	**Human factors**				**System factors**	**Context factors**	**Business factors**	**Interactivity factors**	**Model**	**Application**
	Human roles	**Human demographic attributes**	**Subjective QoE factors**	**Objective QoE factors**						
[21]	X	X	X	X	X	X	X		Framework	Networking
[28]			X		X		X		Framework	Multimedia
[22]	X	X			X		X		Framework	Communication
[29]		X	X	X	X	X		X	Layer	H-M interaction
[24]	X		X	X	X	X	X		Framework	H-M interaction
[23]	X	X	X	X	X	X	X		Framework	Networking
[25]			X		X		X	X	Layer	Multimedia
[26]	X	X	X		X	X	X		Framework	Multimedia
[30]		X	X	X	X	X	X		Layer	NGN
[27]		X	X		X	X	X	X	Framework	NGN
[31]		X	X	X	X	X			Framework	Multimedia

typically done by researchers by conducting subjective quality assessments in which sample people are asked to rate the quality of a service under well defined conditions typically provided by ITU Recommendations [32–34]. Such conditions usually consist in a test environment where the complete end-to-end service is under control and various parameters are varied to add distortions into the service in order to evaluate the influence of such distortions to the quality perceived by the users. The users rate the perceived quality using a well defined quality scale such as the five-level ITU scale, which allows to choose a value from 1 to 5. Specifically, 1 means "Bad quality", 2 means "Poor quality", 3 means "Fair quality", 4 means "Good quality", and 5 means "Excellent quality". The ratings are then averaged to compute the Mean Opinion Score (MOS), which is typically used to represent the QoE of the users.

However, due to the huge number of possible IFs that can affect the QoE of a service, it is very difficult to build a QoE model able to evaluate the impact of each IF into the QoE. Indeed, even considering the most studied services, i.e., the video service, many are the studies proposed in the literature which investigated how the QoE perceived by users watching video sequences is impacted by system IFs, but very few are those considering the impact of other IFs such as interactivity, device, context and human factors [35]. Some of the most relevant works which studied the influence of QoE IFs for video services are discussed in the following.

With regard to system IFs, in [36], the influence of different packet loss rate (PLR), ranging from 0.1% to 10%, affecting video sequences is investigated. The scores assigned by the observers were averaged to obtain the MOS and then collected in a public database. In [37], extensive subjective tests are conducted for assessing the perceptual quality of low bitrate videos, which cover 150 test scenarios and include five distinctive system IFs: encoder type, video content, bit rate, frame size, and frame rate. Based on the subjective scores, a statistical analysis is performed to study the influence of each dimension on the perceptual quality. In [38], a parametric packet-layer model for monitoring the video quality of IPTV services is proposed. The QoE is estimated in terms of the MOS in function of the source coding bitrate and the PLR. This model has been extended in [39] considering also the movement of the video content, and different codecs and video resolutions. Similarly, in [40] a prediction model is proposed for video quality evaluation in terms of MOS which considers the source coding bitrate, the packet error rate, the frame rate and the video content type. In [41], the impact of network impairment on QoE in H.265/HEVC video streaming is studied. The subjective evaluation experiments primarily investigated human perception of the effects of packet loss on HEVC encoded bitstreams. Then, an analysis of the impact of error concealment method, bandwidth, spatial resolution and video content on the perception of quality is also provided. [42] conducted a subjective study to understand human visual QoE of streaming video and proposed an objective model to characterize the perceptual QoE as function of compression distortion, initial buffering, and stalling events. In [43–45], subjective quality assessments are conducted to find a relationship between QoE and KPIs of YouTube videos. [43] defined a quality index function of 3 YouTube performance metrics (initial buffering time, mean rebuffering time and rebuffering frequency) whereas [44, 45] defined a quality index function of the frequency and duration of stalling events.

Not many studies considered the impact of interactivity actions on the QoE perceived when watching videos. Interactivity has been considered for mobile TV service in [46], where the Mobile and Interactive Social TV system (MIST) is presented. MIST allows users to invite other mobile users and create a virtual shared space where users can see and talk to each other while simultaneously watching TV/video content on their mobiles. This system allows for rich interaction modalities such as audio, video and text chat interaction for communication between the users. The study found that the feeling of social presence of people of interest when watching content with them was considered to add value to the viewing experience. Furthermore, users found value in availability of all (in this case audio, video, text) interaction modalities. Accordingly, the interactive TV service proposed in [47] consists in the transmission of extra video or audio streams alongside the main video stream. In [48], user interactivity is considered as the user opportunity of jump forward, backward, pause and resume the video during the playback at any time. Since a standard definition of interactivity is not provided in the literature, from these results it can be stated that interactivity in video services should allow the users to control an application, take decisions on the main contents (change, pause, etc.), and activate extra contents (contents enriching the main application content).

Only a few are the studies regarding the impact of the end device on the QoE perceived when watching videos in the literature. In [49], videos encoded with Scalable Video Coding (SVC) have been evaluated on a mobile phone and a tablet. Experimental results showed that the impact on quality, resolution, or temporal fluidity is more important in bigger size devices (i.e., on tablets) as the dynamics of the lowest and highest values is larger than in case of mobile phones. Furthermore, the frame rate variations were overall scored with lower quality on the mobile phones. In [50], subjective tests were conducted with QCIF videos over two devices: an LCD monitor and a mobile handset. The dataset was generated with a combination of parameters associated with the access network, coding parameters and content types. Final results show that the same conditions gave rise to greater annoyance on a mobile handset than on an LCD monitor. [51] studied the impacts of video resolution, viewing device and audio quality on the perceived audio-visual quality whereas [52] studied the impacts of smartphone configurations (including CPU, screen size and display resolution) on the QoE of end users in the context of multi-party video conferencing.

Therefore, it is evident that QoE modelling is at the very beginning and that it is very difficult to define a QoE model able to provide a mathematical relationship considering the impact of all the IFs on the QoE perceived for a specific service. Indeed, many are the IFs to be considered, which vary for each different service and scenario. Additionally, each modelling approach starts from some assumptions which have to be matched when using the model in order not to drive the application design and/or deployment towards wrong directions. Moreover, the definitions of the models and their factors often follow different approaches, making it difficult to compare the proposed methods and to combine their results in the effort of achieving better performance.

QoE models for the Internet of Things

The IoT refers to a network of interconnected objects that are able to acquire information from the physical world and to make this information available on the Internet. It is possible to basically identify three generations of IoT on the basis of the involved technologies [53]. The first one was developed around Radio-Frequency IDentification (RFID) tags, which were typically used for monitoring, logistics and tracking applications. The second generation was enhanced by sensors and actuators, which permitted acquiring various physical characteristics from the real world and brought to birth of Wireless Sensor Networks (WSN), which consist of a certain number of sensing and/or actuating nodes communicating in a wireless multi-hop fashion [54]. The third (and current) IoT generation is mostly developed around the association of a virtual object to each physical object. The virtual object has the role of virtualizing the functionalities of the physical object, which is then part of the IoT. Everyday physical objects become *smart* objects and are integrated within the global cyber-physical infrastructure [55]. Furthermore, the storage of the data and running of the application have been moved to the cloud. From the second generation forward, multimedia devices have been playing a more and more important role in the IoT as the physical devices augmented with the virtual counterparts have become more powerful in the generation, processing and transmission of multimedia data.

Even if many IoT architecture have been proposed in the literature, there is not a reference IoT architecture yet [56]. The basic proposed architectures were based on 3-layer models consisting of the Application, Network, and Perception layers [57–59]. [60] and [61] considered and additional layer for cloud computing. Recent proposed architectures have taken into account the virtualization and abstraction concepts of the third IoT generation by considering additional layers such as Middleware, Service Composition, Service Management, Object Abstraction as well as Business layers [53, 62, 63]. Also some projects, such as IoT-A [64] and iCore [65], designed an IoT architecture based on the concept of virtual object and service management, accounting for the needs of researchers and the industry. A specific implementation of an IoT solution that follows this model is the Lysis architecture [66].

Briefly, IoT will be populated by an immense number of devices. Such devices will adopt heterogeneous technologies and standards and will have unequal capabilities in terms of processing, communication and energy availability. However, they will provide services integrated in critical applications involving the continuous monitoring and control of the physical environments in which humans live and operate. Size, heterogeneity, the criticalness of the envisioned applications and the limitations of the resources of the components make the IoT a very complex environment, rich with opportunities and threats. It is unlikely that even the most advanced of the IoT devices will be able to survive and operate effectively in such a context, individually. IoT platforms have then the objective to combine and control the flows of traffic and signals received from different objects, processing in real time and offline the data and take actions, which will impact at the end (hopefully in a positive way) the quality of life of the humans. In this scenario, the evaluation of the performance of IoT applications is becoming more and more important as relevant deployments are ubiquitously present in our everyday life activities. However, the plethora of IoT applications is quite vast, so that giving some guidelines on how to conduct this evaluation is very complex in a fast changing setting. Some studies related to this issue have been conducted with reference to the QoS evaluation models for IoT applications. For instance, in [58, 59], for the 3-layer IoT architecture, monitoring modules are defined to manage the resource allocation as a function of the measured QoS metrics: information accuracy, sensing precision and energy consumption at the Sensing layer; bandwidth, delay, throughput and coverage at the Networking layer; service performance cost, performance time, load and reliability at the Application layer. Although QoS parameters are important for the performance evaluation of an IoT platform, they should be considered as a function of the quality perceived by the end-user, i.e., the QoE, and not only as a fulfillment of SLAs.

Being user-centric, the QoE provides a more holistic understanding of the system's influence factors with respect to the technology-centric measures of the QoS approach. Being closer to the user perspective, it better provides indications of to what extent the applications will be used by the users and what will be the real impact on the human quality of life. As discussed in Section 2.1.1, the QoE is defined as *"the degree of delight or annoyance of the user of an application or service."* [6]. Such a definition of QoE is valid for general multimedia applications and services; therefore, it can also be extended to IoT applications. However, currently, there is no reference model for evaluating the QoE of IoT applications, probably due to the lack of a reference IoT architecture and to the different requirements of IoT applications belonging to different domains of utilization. Indeed, there are only a few works that have started addressing this issue. In [67], the authors focused on the perceived quality in actuators connected to the IoT.

They developed a test bed that consisted of an electro-mechanical arm controlled over a packet switched unreliable link. The experiment required users to direct a fixed laser attached to the fixed arm's grabber towards a set of targets. The experimental factors were the average one-way delay, the packet loss and the number of degrees of freedom of the arm. From the subjective quality results, in terms of the MOS, the authors defined a parametric QoE model that estimates the QoE as a function of the considered experimental parameters. While [67] focused on a specific IoT application, in [68] the authors defined the Cognitive Internet of Things (CIoT), a new network paradigm where physical and virtual things or objects are interconnected and behave as agents, with minimum human intervention. The CIoT framework measures three different qualities: Quality of Data (QoD), i.e., the quality of sensed data; Quality of Information (QoI), i.e., the information that meets a specific user's need for a specific time, place and social setting; QoE, focused on factors belonging to four levels: access, communication, computation and application. In [69], a framework of scalable QoE modelling is proposed, which models the QoE as a 4-layer QoE model consisting of Device, Network, Computing, and User layers. Two types of quality metrics are considered: physical and metaphysical metrics. Physical metrics express the massive amount of quality metrics of the IoT architecture, such as network QoS, sensing quality, and computation quality. Metaphysical metrics express quality metrics that users of applications demand, such as context information and comfortable service. By aggregating the massive amount of physical metrics into certain metaphysical metrics, the QoE is modelled as a function of quality metrics in the IoT architecture.

It can be noticed that both the proposed IoT architectures and quality evaluation models follow a layered approach to consider different influence factors within each layer. In the literature, several works grouped *related* QoE influence factors into well-defined domains, spaces or layers. For example, the ARCU (Application Resource Context User) proposal models QoE influence factors as falling into one of four multi-dimensional spaces: Application, Resource, Context and User [26]. Points from the ARCU space are then mapped (with objective models or subjective evaluations) to points in a QoE space, which is composed of dimensions representing different quantitative and qualitative quality metrics, which can be perceived by an end-user (e.g., MOS, ease-of-use, efficiency, comfort). The theoretical approach defined by the ARCU model was used in [70] to define an operational approach: the QoE layered model. The six layers defined by this model basically respect the spaces defined by the ARCU model. However, two spaces were further modeled: the context space is represented by the interface and the context layers, while the user space is represented by the human and the user layers. In [71], the hourglass model is proposed, which is composed of four layers: QoS; Quality of Delivery, i.e., the quality of data delivered by both the application and the network; Quality of Presentation; QoE. As is common for layered approaches, each quality estimation is in turn implemented utilizing the quality estimation provided by the previous bottom layers. Therefore, starting from the QoS, the authors defined the functions which brought to the estimation of the QoE. The layered approach was also used in [72] to model the proposed QoS/QoE management framework into the Data acquisition, Monitoring and Control levels. The authors mainly focused on the management component of the framework to show how data collected from a network can be refined into knowledge of quality perceived by users and how to take corrective measures when necessary. Although QoE management frameworks have been also proposed for cloud applications [73] and future Internet architectures [74], to the best of the author's knowledge, no studies have focused on QoE management for IoT applications.

Moreover, it is worth mentioning that since 2008, the MPEG group has been working on a standard called MPEG-V (ISO/IEC (International Organization for Standardization/International Electrotechnical Commission) 23005) [75–77], which aims to define a standard way of representing the data from sensors and actuators in the real world, as well as a common interface to virtual worlds. As a result, each proprietary virtual world will not be isolated from the other virtual worlds. In particular, MPEG-V defines the XML schema for the information about sensor/actuator capabilities, user preferences, sensed information and data types used by actuator commands. These data type elements correspond to descriptions of devices and messages for *talking to* and *adapting to* either devices or services in the IoT. In addition, the Part16 of MPEG Exploration (called Internet of Media Things and Wearables (IoMT & W)) is trying to understand IoT requirements that are not yet satisfied by MPEG-V [78]. Therefore, in this draft, the media-centric Internet of Things is defined, as *"the collection of interfaces, protocols and associated media-related information representations that enable advanced services and applications based on human to device and device to device interaction in physical and virtual environments"*. Furthermore, the definition of media thing is introduced, as *"a Thing with at least one of audio/visual sensing and actuating capabilities"*. The scope of IoMT & W is to standardize a set of interfaces, protocols and associated media-related information representations. However, to date, only media thing requirements and some use cases have been defined. Furthermore, MPEG-V does not consider any module for the evaluation of the quality provided by its proposed framework.

State of the art works are very limited with regard to quality evaluation and management of IoT architectures and applications. The major obstacles are the lack of a reference IoT architecture and the different requirements of IoT applications belonging to different domains of utilization. However, due to the increasing importance and spreading of IoT platforms, there is the need to define QoE models which are able to measure and manage the QoE of IoT applications. The definition of a layered model seems to be the optimal approach for achieving this objective.

2.2 QoE application scenarios

In the last years, QoE has been considered in many emerging application scenarios. Some examples are vehicular networks, smart cities, smart homes, smart space, interactive multimedia, mulsemedia, 5G networks, etc. In vehicular networking, P2P content sharing for multimedia streaming services has rise to the challenge of supporting high QoE for interactive Video on Demand (VoD) mobile service [8, 9]. Multimedia delivery over wireless networks is facing the issue of limited battery life of mobile devices, particularly when multimedia applications are run for which users have high quality expectations. In [79], a cross-layer quality-oriented energy-efficient multimedia delivery scheme is presented, which balances the need for increased energy efficiency/battery lifetime and high user QoE. Mulsemedia services regard emerging multiple-sensorial media services, which involve different media components than the traditional multimedia applications, such has haptic, scent, airflow, etc. [10]. [11] conducted a detailed study on how mulsemedia content affects user QoE as perceived by the users subjected to multisensorial stimuli. The advent of 5G Networks introduces significant challenges in almost every link of the network value chain [80]. [12] proposed a data-driven architecture for enhancing personalized QoE for 5G networks. [81] defined a virtual probe for QoE monitoring whereas [82] proposed a method that measures the user's QoE for video streaming traffic using the network QoS parameters. Smart Cities challenges regard not only to ensure high performance with respect to the node mobility and the energy consumption but also to guarantee high levels of QoE perceived by the end-user. [13] provides an initial research on how QoE service provision will impact the development of smart city services. A smart space is a physical space equipped with sensors, actuators, and pervasive devices. QoE of smart space refers to the factor of human impact on design and is associated with user perception, experience, and expectations of application and network performance [83].

In the following, a background on two specific QoE application scenarios is provided. Specifically, in Section 2.2.1 past studies are discussed regarding QoE-aware management approaches for multimedia services considering the collaboration between Internet Service Providers (ISPs) and Over The Top (OTT) services. Furthermore, in Section 2.2.2 past works proposing QoE-aware Smart Home Energy Management (SHEM) systems are discussed.

2.2.1 QoE-aware collaboration between OTTs and ISPs

It is a matter of fact that the proper management of QoE brings to direct economic advantages; in fact, if a customer does not receive adequate QoE, it is more likely to become a churner. According to the study conducted in [84], quality and pricing are considered as major causes for a user to become churner. Nowadays, the users' satisfaction related to a particular service plays an important role in the growth of market share of any company dealing with multimedia services and it has high cross correlation in the prediction of users' churn as well. Indeed, survey results showed that around 82% of customer defections are due to frustration over the service and inability of the operator to deal to this effectively [85]. Moreover, frustrated customers will tell other people about their bad experiences, resulting in negative publicity for the provider. It is also important to note that most of customers do not complain before defecting but they simply leave once they become unsatisfied. Therefore, it is very important that providers investigate user's expectations and constantly monitor delivered quality to prevent the user churn. From another survey, 20% of respondents reported that they would immediately leave a company because of poor service experience [86]. But most importantly, it resulted that the number of customers who leave because of poor customer experience is significantly higher than the number of those who leave a business because they found a lower price elsewhere: 68% versus 53%. Therefore, service quality has more influence on the user churn than price. For these reasons, delivering good QoE helps to contrast the user churn and increase the revenue.

However, although network and application providers share the common objective of providing better service quality to their customers, to date, research in this field is divided into two separate paths: on the one hand network-aware application management approaches aim to adapt the delivery of multimedia contents on the best effort over the network by inducing change in the application parameters on the basis of the monitored network status [87]; on the other hand, application-aware network management approaches focus on effective management of network resources according to application requirements [72]. However, the drawback of the above mentioned research stream is that OTTs have no control over network for enhancing users' QoE, whereas ISPs have no availability of application model neither encrypted content nor users' privacy allow them to go for Deep Packet Inspection (DPI) [7]. Hence, both the ISP and the OTT cannot deliver the best QoE to their valued customers, which results into user churn as well as decrease in market shares. Therefore, optimal end-to-end QoE-based service delivery can only be possible if OTT and ISP collaborate and agree upon a common QoE-based management approach and exchange of the QoE-oriented information. Since the OTT is more QoE-oriented, its role in the collaboration may be the monitoring of the QoE perceived by the users. By sharing this information with the ISP, this may be able to manage the network in a more QoE fashion than by using QoS-to-QoE models. By following a joint service management paradigm, both the entities may overtake their limitations in QoE management: the ISP can manage its network in a QoE fashion and the OTT can base on the ISP if better network resources are needed for service delivery.

Although the collaboration among OTTs and ISPs is catching the eyes of researchers working in QoE-oriented service management, still only few works have really addressed this aspect in the literature. The importance of the collaboration between network providers and applications in the future Internet is addressed in [88], by discussing a scenario in which applications give more information about their needs and network usage so that ISPs can allocate network resources more efficiently or even open their network so that applications can dynamically invoke some network services. Two existing collaboration techniques are discussed: ALTO (Application-Layer Traffic Optimization) [89] and CINA (Collaboration Interface between Network and Application) [90]. The ALTO initiative allows P2P networks and ISPs to cooperate in order to optimize traffic being generated by P2P applications and transported over the ISPs infrastructure. However, the application-ISP interaction in ALTO only concerns network information provided by ISPs and processed by applications, i.e., the ISP is blindfolded to the services which their customers subscribe to. These limitations are addressed by the CINA interface, which not only allows applications to retrieve information about the network, but also offers the possibility to instantiate network services such as multicast service, caching nodes, and high capacity nodes. Nonetheless, these works are specific for P2P applications and the collaboration between network and application is limited. Furthermore, business aspects are not investigated and the management is not centered on the QoE.

With regard to the multimedia industry, the most common form of collaborations agreements between OTTs and ISPs are QoS-based and can be classified into two categories: peering and surrogate servers. Indeed, most of OTT services use different Content Delivery Networks (CDNs) for the decentralization of the contents so that these are located near to the users on a regional basis in order to lower the content retrieval latency. A recent form of collaboration between OTT and ISP can be seen as the ISPs peering with the CDNs of the OTTs. On the basis of peering policies, peering agreements between OTT and ISP can be classified as Settlement-Free-Interconnection (SFI) and Paid-peering, where the former is the most used peering strategy. Technically, the peering can be categorized as 1) Direct or Private Network Interconnection (PNI) and; 2) Public Peering Interconnection (PPI) through the Internet eXchange Points (IXPs). For example, YouTube video streaming is mostly delivered by Google CDNs, which are connected to the Google core data centers [91]. Google provides both PNIs and IXPs based peering to ISPs based on SFI peering policy with two different Google Autonomous Systems (ASs), which provide a complete set of Google services (common peering option) and a subset of Google's most popular content (available at a small number of locations). Similarly, for Skype, Microsoft is providing SFI based PNIs and IXPs peering connections where the peer should declare all the routing paths and Microsoft carries traffic optimization for the Skype generated traffic on the basis of network latency [92]. In the case of Netflix, there are several SFI based open peering PNIs and IXPs connections for the ISPs; however ISP ready for the peering agreement needs to join Netflix Open Connect Program, whose purpose of peering is not only to provide better connection between Netflix's CDN and ISP but also to move the most popular content near to end users in the host's network with Netflix's surrogate servers called embedded Open Connect Appliances (OCAs) [93].

Moreover, nowadays OTTs normally provide the hosting ISP with surrogate servers (replicas of the original web server), which can be installed inside the host network to provide the contents near to the end users. The selection of the content is based on the usage trends which are known to the OTT. The surrogate servers provide mutual benefits for the two providers: by decreasing the transit requests, the ISP decreases transit costs as well as the network overload in the backbone network; furthermore, it allows to deliver the OTT contents with less latency than just a simple peering. Most of the surrogate servers based collaborations found in the industry are settlement-free where none of the parties pay each other but they agree on mutual benefits. An important case is the one of Google that is providing Google Global Cache (GGC) edge nodes to ISPs with more Google's applications (YouTube, Google Play, Google Search, Google Maps etc.), which are capable of treating from 60% to 80% of the traffic generated by Google's application [91]. Another is the case of Microsoft that is providing surrogate servers to ISPs for Skype services [92], whereas Netflix is providing the collaborating ISPs with OCAs surrogate servers under Netflix Open Connect program [93].

Therefore, state of the art collaborations between OTTs and ISPs are limited, i.e., some are specific for P2P applications whereas others are based on QoS optimization rather than considering the user perceived quality to deliver better service quality through peering and surrogate servers. To address these limits, there is the need to investigate how the ISP and OTT may collaborate for QoE-oriented service management through the optimization of both network and application resources.

2.2.2 QoE-aware Smart Home Energy Management systems

Smart Homes are characterized by the presence of smart devices, which give the opportunity to monitor and to remotely control key equipment within homes with Smart Home Energy Management (SHEM) systems. In such an intelligent environment, one of the major goals is to provide decision-support tools in order to aid users in making cost-effective decisions when utilizing electrical energy. As a matter of fact, nowadays domestic electricity usage accounts for 30% of the global energy consumption and usage awareness and scheduling optimization alone have the potential to reduce consumption by 15% in private households [94]. However, also the quality (i.e. comfort) perceived by final users when policies are put in place is crucial for wide user acceptance and pertains to the domain of QoE.

Currently, most of the literature considers the customer comfort as a set of hard constraints on appliance usage, a priori set without profiling among different kinds of customers, which are likely to have different subjective needs. For example, in [95–98], SHEM algorithms with user preset priorities on household loads are used to keep grid power consumption below a certain level. Appliances are classified based on the priority given by users to each load regardless of the day of the week and the time of the day in which are used. In [99], an algorithm for Distributed Energy Resources (DER) is proposed to reduce power consumption and minimize appliances execution shifts and turn off actions based on the priority class they belong to. Consequently, customer comfort is evaluated as the minimization of appliances turn-off operations, but no profiling is considered for different user types. In [100], end users assign values to energy services so that DERs (the only energy supply considered) are scheduled based on these preferences in order to coordinate their optimization and turn off appliances with lower priority at first. In [101, 102], an algorithm that takes into account the tradeoff between customer comfort and cost of energy, by setting minimum and maximum boundaries for the thermal comfort is presented. These boundaries are taken as hard constraints for a priori setting but a background on customer comfort profiling lacks.

Moreover, emphasis is often put on the cost or energy optimization, but no metrics for a posteriori evaluation of the perceived quality is given, which is instead a widely exploited concept in the QoE domain. For instance, in [103], a mathematical model to optimize the control of all major residential energy loads together with Renewable Energy Sources (RES) is proposed. Comfort levels are defined as the preferred hours for using appliances and as the maximum allowed shift from the preferred time. However, similarly to the above mentioned works, hard constraints are considered and no a posteriori evaluation as well as customer profiling are given. [104] proposes a multi-agent architecture for optimal energy management in smart homes considering grid power supply. Customer comfort is considered as a thermal comfort zone delimited by hard boundaries which must not be left, similarly to [101]. With respect to the previously cited works, [105] and [106] introduce a demand-response optimization algorithm in which energy usage and power cost are optimized over a neighbourhood rather than for a single household.

Only few papers took QoE-awareness into consideration for resource allocation. In [107], QoE is used to drive resource allocation but in the multimedia communications domain. [108] designed a home gateway able to determine in real time the QoS requirements of applications and accordingly make routing decisions to optimize QoE of the end user. However, this is most focused on smart multimedia devices and does not consider energy consumption and user preferences. [109] proposed an adaptive QoS framework on Android to enhance the QoE of applications in wireless home networks, and specifically of home-media sharing services on various inter-operable DLNA-enabled audio/video terminals. In [110], a Dynamic Balancing Quality Control Model (DBQCM) is presented, which consists of a SHEM system and QoS and QoE quality measures which are used to train the model. In [111], a QoE-driven power scheduling strategy for SHEM is presented. However, the QoE model is based on objective measures (power price and power consumption) rather than subjective quality assessments, as required by the definition of QoE itself.

The works proposed in the literature are limited in that for energy management the customer comfort is set a priori as a set of hard constraints on appliance usage without profiling among different kinds of customers. Furthermore, the proposed algorithms are focused only on energy optimization and a posteriori evaluation of the perceived quality is not considered. Additionally, any study considered the QoE for users profiling and as a metric to drive the energy management as well as a measure for a posteriori evaluation of the customer comfort.

Chapter 3

QoE modelling

Quality of Experience (QoE) modelling aims to define the relationship between different measurable QoE influence factors (IFs) and quantifiable QoE dimensions for a given service scenario. Such models serve the purpose of making QoE estimations, given a set of conditions, corresponding as closely as possible to the QoE as perceived by end users [7]. The perceived QoE is typically evaluated by organizing subjective quality assessments in which sample people are asked to rate the quality of an application or service. Though, these are time consuming and unsuitable for real-time applications (e.g., quality monitoring). Thus, objective QoE models are preferred, which can be used in QoE management systems to predict and optimize the end-user QoE. Many QoE models have been proposed in the literature, which consider several IFs and follow different modelling approaches making it difficult to compare the proposed methods and to combine their results in the effort of achieving better performance. This has brought to the issue of modelling un-interoperability, i.e., the unfeasibility of integrating the results of different modelling activities to broaden the range of scenarios where the integrated model can be applied.

In Section 3.1, a layered model for evaluating the QoE of multimedia services is proposed, which aims to address the issue of modelling un-interoperability. The layered model allows defining each layer singularly and independently from the others so that each layer analyzes a specific QoE domain (set of IFs) and the overall quality can be computed as a combination of all domains. To demonstrate the validity of the proposed layered model, in Section 3.2 the influence of system IFs (coding and transmission parameters) on the QoE perceived by the users when streaming video sequences over lossy wireless channel and played back on tablet devices is analyzed. Then, in Section 3.3 the influence of interactivity on the QoE perceived when streaming video on tablet devices is analyzed. The aim is to go further in the analysis of the importance of the interactivity by conducting subjective assessment tests aimed at isolating the contribution of the relevant features on the final QoE with respect to system IFs. Thereafter, the contributes to the QoE perception provided by system and interactivity IFs are combined for the estimation of the overall QoE.

In Section 3.4, the influence of the device switching on the quality perceived by users watching video contents is investigated. Device switching means that the user starts watching a video sequence on a device, and at a specific moment (called switching time), the video is streamed on a different device in which the user continues watching the video. The aim is to demonstrate that the QoE is not only related to the video consumption on the single device, but it takes into consideration the overall experience of watching the whole video by switching between different devices; for this reason, two devices with very different characteristics and technical capabilities were deliberately chosen, i.e., a TV screen and a tablet.

In Section 3.5 a first approach on QoE modelling for the Internet of Things (IoT) is discussed. Firstly, a reference IoT architecture is analyzed to provide guidelines on which IFs should be considered and measured for the evaluation and management of the QoE of IoT applications. Secondly, the concept of Multimedia IoT (MIoT) is introduced in order to focus on the applications in which people are involved as the end-users of the multimedia content provided by the MIoT applications. Thirdly, a layered QoE management framework is proposed, which aims at evaluating and controlling the contributions of each IF to estimate the overall QoE in MIoT applications. Finally, as a practical use case, a vehicular MIoT application is implemented that has been used to conduct subjective quality assessments to verify the applicability of the proposed approach.

Finally, Section 3.6 concludes the Chapter.

3.1 Layered QoE model for multimedia services

Given the huge number of variables to be considered when defining a QoE model, the proposed solutions have typically a limited applicability in terms of network settings (e.g., bandwidth and introduced impairments), system settings (e.g., codec, error concealment algorithms), as well as in terms of adopted user terminal. Additionally, each modelling approach starts from some assumptions which have to be matched when using the model in order not to drive the application design and/or deployment towards wrong directions. Furthermore, each solution considers and proposes its own definition and classification of QoE IFs. Indeed, from the analysis conducted in Section 2.1.2, with regard to the state of the art QoE models analyzed in Table 2.1, it follows that the set of QoE IFs to be considered to achieve an effective QoE evaluation include different domains: human, system, context, interaction, and business. Models that do not include factors from all of these domains would result in limited applicability. However, looking at the works that have been defined in the last years, it can be observed that the focus is mostly on a limited subset, frequently due to a specific application scenario. Additionally, the definitions of the models and their factors often follow different approaches, making it difficult to compare the proposed methods and to combine their results in the effort of achieving better performance. This has brought to the problem of modelling un-interoperability, which is herein defined as the unfeasibility (or at least difficulty) of integrating the results of different modelling activities to broaden the range of scenarios where the integrated model can be applied.

In summary, from the state of the art in quality modelling the following issues are observed:

- The definitions of the quality domains are often vague so that each work considers different factors. Though the core definitions of the domains (system, human, and context) are similar, their borders are not well-defined so that they overlap with others, making it unclear.
- Comparison of the different proposals is difficult, since different approaches are followed, e.g., the way the different factors are considered and at which stage of the modelling.
- Results coming from different experiments are difficult to be combined in the attempt of extending the significance of the joint studies; this is due to the fact that different impairments are combined in different ways and with different meaning.
- Incremental modelling is difficult as a consequence of the previous points.

Moreover, in the following, three examples of inconsistencies related to the definition of the IFs are provided:

- in [27], usability and expectations IFs are modelled as key domains while in [21, 23, 26] they are modelled as attributes of the human domain, specifically, as human subjective IFs.
- in [21, 23, 28] the business factor is considered as one of the main domains, while in [24–27] business/economic factors are considered as attributes of other domains (generally of the context domain).
- in [30], human objective quality factors are represented with information describing service and content factors, while in [23, 28] they are related to physiological, psycho-physical, and cognitive capabilities.

To solve these inconsistencies, the definitions provided in the Qualinet white paper for system, human, and context IFs are considered [6]. Indeed, notwithstanding these definitions are not provided by a standard entity as the ITU, they are widely accepted and used as a reference by researchers working on the QoE area. The reason is that a large number of authors and editors with high experience on the QoE concepts contributed to the writing of the Qualinet white paper. Accordingly, the business IFs are considered as part of the economic context (see Context IFs). Additionally, interactivity IFs are also considered and their definition is provided in this thesis since there is not a reference definition for interactivity in the literature.

In the following, the definitions of the considered QoE IFs are provided:

Human IF: is any variant or invariant property or characteristic of a human user. The characteristic can describe the demographic and socio-economic background, the physical and mental constitution, or the user's emotional state.

System IFs: refer to properties and characteristics that determine the technically produced quality of an application or service. They are related to media capture, coding, transmission, storage, rendering, and reproduction/display, as well as to the communication of information itself from content production to user.

Context IFs: are factors that embrace any situational property to describe the user's environment in terms of physical, temporal, social, economic, task, and technical characteristics.

Interactivity IF: interactivity actions allow the users to control an application or service, take decisions on the main contents, and activate extra contents (contents enriching the main application content).

On the basis of these considerations, a layered model is suggested. Layered approaches are widely used in networking for their functionality. The TCP/IP and OSI networking models, for instance, are organized as a set of functional layers. Within each of these layers, a well-defined set of network services are provided, which are in turn implemented utilizing the services provided by the previous layers. At the lower layers, services tend to be simple and efficient. As successively higher layers are considered, functions become gradually more complex. Then, users and applications can operate at the lowest level that provides the required degree of service, without the overhead of more complex and unnecessary features. Following this layered approach, each layer must be defined together with its area of competence. In this case, each layer must model the quality provided by a certain domain. Furthermore, each layer must be able to be combined with its upper and lower layers; this feature is fundamental in order to build a model in which the outcome of a layer can be interpreted and then gradually enhanced by higher layers. For such reason, interfaces between layers should be accurately defined.

The layered model allows defining each layer singularly and independently from the others. Each layer analyzes a specific QoE domain (set of IFs), so that the overall quality can be computed as a combination of all domains. The proposed model is meant to be as general as possible, so to be valid for, or at least adaptable to, any scenario. An advantage of the layered approach is that existing quality metrics can be used to measure the quality within specific layers; for instance, at the media layer existing objective media quality metrics can be used to evaluate the quality of media signals.

In order to define the domain for each layer, it is considered the fact that in the last years multimedia services have become more immersive: they generally provide more than two media contents and may offer elaborate interactivity. Furthermore, the context of consumption has become increasingly important, as it includes the use of mobile/fixed devices, different business models, etc. Therefore, there is the necessity to evolve from the traditional quality model which considers a fixed context, simple interactivity and one or two media, to a new model which takes into account multi-parameter contexts, complex interaction and real multimedia.

Figure 3.1 shows the proposed layered QoE model, which is composed of 5 layers:

1. **Components layer:** focuses on media quality, accounting for system IFs regarding each single media composing the multimedia signal.
2. **Combination layer:** aims at evaluating the integration functions which quantify the multimedia signal quality, i.e., how single media qualities are combined to obtain the overall multimedia quality.
3. **Control layer:** accounts for the control and interactivity features and user actions on multimedia contents. Interactivity IFs are considered in this layer.
4. **Context layer:** considers the influence of context IFs on the perceived quality.
5. **Human layer:** human IFs are accounted in this layer.

The major advantage of the proposed approach is that each layer focuses on IFs belonging to a specific quality domain, and the evaluation of the relevant impact can be conducted independently from that related to others quality domains. This allows conducting independent experiments in different times and places and combining the individual quality results in order to estimate the overall QoE. Although the proposed approach is mostly meant for the measurement and modelling of QoE, it could be easily applied in QoE-aware system design. The automatic adjustment of system parameters to ensure optimal user satisfaction at all times is indeed an extremely challenging problem. Nonetheless, the less quantifiable factors, mostly related to context, business and interaction, could be considered in the QoE managing frameworks in a way comparable to more classical factors such as the coding bitrate, once correctly

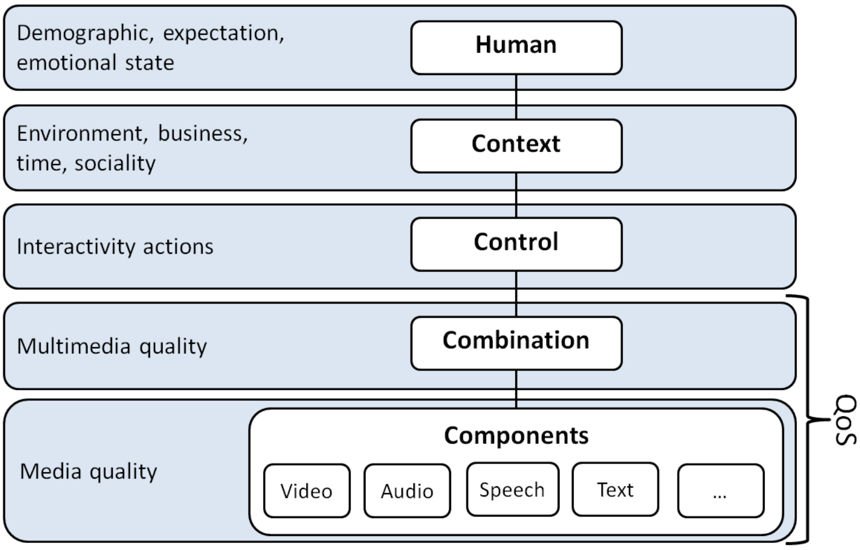

Figure 3.1: Proposed layered QoE model for multimedia services.

modelled. Interactivity, for instance, could be part of a QoE feedback mechanism, allowing for switching on/off the interactive functionalities based on the measured QoE and a trade-off between performance and complexity.

However, is this approach valid? Or are quality domains irremediably entwined? Experimental results are needed to demonstrate the validity of the proposed strategy. Then, specific subjective quality assessments need to be conducted so as to validate the hypothesis of quality domains differentiation and isolation. The experiments should be focused on evaluating the quality contribution relative to each domain; subsequently, all contributions should be combined in order to investigate whether their combination provides a reliable estimate of the overall quality. Clearly, this calls for extensive experimentation. In this thesis, some preliminary results are reported, with a particular focus on the video streaming service. Specifically, in Section 3.2 the influence of system IFs is evaluated, by considering the impact of a wireless lossy channel on the QoE perceived when streaming video on tablet devices. From subjective results a QoE model is derived, which estimates the QoE perceived in function of the considered system IFs. Then, in Section 3.3 the influence of interactivity on the QoE perceived when streaming video on tablet devices is analyzed. Subjective assessment tests are conducted, which aims at isolating the contribution of the relevant interactivity features on the final QoE with respect to system IFs. Finally, the contributes to the QoE perception provided by system and interactivity IFs are combined for the estimation of the overall QoE so as to investigate whether the proposed layered model is valid.

3.2 QoE perception when streaming videos: the impact of system IFs

In this section, the influence of system IFs on quality perception with regard to video streaming services is investigated. Specifically, the QoE perceived when video sequences are transmitted over lossy wireless channel and played back on tablet devices is analyzed. In a real video streaming transmission over lossy wireless channel, the received video sequences are degraded versions of the original ones, due to the lossy coding and the channel transmission errors. Then, the annoyance caused by various distortion effects on the received video sequences may vary greatly depending on the introduced distortion. In this study, 216 distorted video sequences are generated by combining encoding (bitrate) and transmission (playout delay, packet loss rate, starvation occurrences (transmission interruption)) parameters. Then, 40 subjects rated the quality of the distorted video sequences. Finally, from subjective results QoE parametric models are defined.

3.2.1 Test video sequences

Four twenty-second-long YUV video sequences at CIF (Common Intermediate Format) spatial resolution were considered as the original video sequences [112]. Then, 54 distorted video sequences were generated from each original sequence to simulate the video streaming transmission over an error-prone channel. Table 3.1 illustrates the values of encoding (bitrate) and transmission parameters that were combined to generate the distorted video sequences. The bitrate values have been selected to determine two different video qualities: low (200 kbps) and high (400 kbps). The videos were coded with the JM18.0 version of the H.264/AVC reference software [113] and then packaged in the MP4 format container. Table 3.2 illustrates the chosen encoding parameters. The playout delay causes a delay at the beginning of the video playback from the instant in which the user selects to start watching the video, which is set to 0, 3, or 6 s. The buffer starvation causes an interruption in the playback, which is partially masked by freezing the video to the last decoded frame. These events are inserted randomly in the video sequence and last for a time period of random length (following a Gaussian distribution with average of 1 s and standard deviation of 1 s). These events simulate the condition of playback buffer underflows determined by peaks in the network latencies and can occur 0, 1, or 3 times in the proposed distorted videos. The PLR errors generation is based on the *transmitter simulator.exe* software [114, 115]. This software discards a selected percentage of packets from the compressed H.264 bitstreams, to simulate the packet drop introduced by a lossy wireless channel. This is done through the definition of two error pattern files corresponding to PLRs of 0,

Table 3.1: Values of the encoding (bitrate) and transmission parameters used to generate the distorted video sequences.

<table>
<tr><th>Parameter</th><th>Acronym</th><th colspan="6">Value</th></tr>
<tr><td>Bitrate (kbps)</td><td>Rate</td><td colspan="3">200</td><td colspan="3">400</td></tr>
<tr><td>Playout delay (s)</td><td>PD</td><td colspan="2">0</td><td colspan="2">3</td><td colspan="2">6</td></tr>
<tr><td>Starvation (# of occurrences)</td><td>STRV</td><td colspan="2">0</td><td colspan="2">1</td><td colspan="2">3</td></tr>
<tr><td>Packet Loss Rate (%)</td><td>PLR</td><td colspan="2">0</td><td colspan="2">0.4</td><td colspan="2">3</td></tr>
</table>

Table 3.2: Values of the encoding parameters.

Encoding parameter	**Value**
Frame rate	24 fps
Number of frames	480
Profile	Extended
Chroma format	4:2:0
GOP size	16
GOP structure	IBBPBBPBBPBBPBB
Number of reference frames	5
Entropy coding method	Universal Variable Length Code (UVLC)
Slice mode	Fixed number of macroblocks
Rate control	Enabled
Macroblock partitioning for motion estimation	Enabled
Motion estimation algorithm	Enhanced Predictive Zonal Search (EPZS)
Early skip detection	Enabled
Selective intra mode decision	Enabled

0.4% and 3% according to [116]. The impact of the errors depends on the coding configuration adopted. Each frame is divided into a fixed number of slices, where each slice consists of three full rows of macroblocks.

A dedicated wireless LAN is used for the video streaming to the final users so that no additional impairments are introduced. Indeed, all the configurations discussed above have been simulated so as to have a complete control of the assessment environment. With such *ideal* wireless channel, the artifacts visible in the decoded video sequences should only depend on the streaming simulation process previously described. Then, the distortion parameters can be controlled so to achieve more specific results in the subjective assessment.

3.2.2 Subjective evaluation procedure

For QoE evaluation, a subjective quality assessment has been conducted with the help of 40 subjects that were asked to rate the quality of the 216 distorted video sequences. For subjective tests, specifications given in [34] were adopted. Specifically, the single-stimulus Absolute Category Rating (ACR) method has been used, which consists in presenting the test sequences one at a time and allowing for their independent evaluation on a category scale. The following five-level ITU scale for rating overall quality has been used: 5 stars (Excellent), 4 stars (Good), 3 stars (Fair), 2 stars (Poor), 1 star (Bad). The scores assigned by the observers are averaged in order to obtain the Mean Opinion Score (MOS).

Two tablets were used for watching the videos: an Apple iPad 2 and a Samsung Galaxy Tab, whose technical specifications are:

1. Apple iPad 2
    - display: 9.7″ diagonal, 1024×768 resolution, 132 PPI
    - operating system: iOS 5.0.1
    - browser: Safari.
2. Samsung Galaxy Tab GT-P1000
    - display: 7.0″ diagonal, 1024×600 resolution, 170 PPI
    - operating system: Android v2.2
    - browser: Browser v2.2

Two websites have been implemented for the display of the video sequences and the scoring procedure: a website for the iPad 2 and a website for the Galaxy Tab. The iPad 2 website makes use of the HTML5 language which natively supports video sequences in the MP4 format. Both website and distorted video sequences reside on the University server. The Galaxy Tab website is based on the Flash technology, which allows for retrieving the video sequences from YouTube servers by specifying the unique video code. In the latter case, all distorted video sequences are uploaded in a private YouTube channel. The choice of implementing two different solutions derives from the need for using the best technology for each terminal. HTML5 is the optimal choice in case of the iPad 2, since it allows for accessing the video sequences from our servers, thus gaining complete control over the transmission; additionally, iPad 2 does not provide support for the Flash technology. As to the Galaxy Tab, Flash presents good reliability and the YouTube channel provides good throughput performance. The two implementations have been extensively checked before conducting the subjective tests. The final results seem to confirm such choices, since the judgments for the two devices do not show any significant gap on average. Moreover, such difference is transparent to the subjects; in fact, both websites

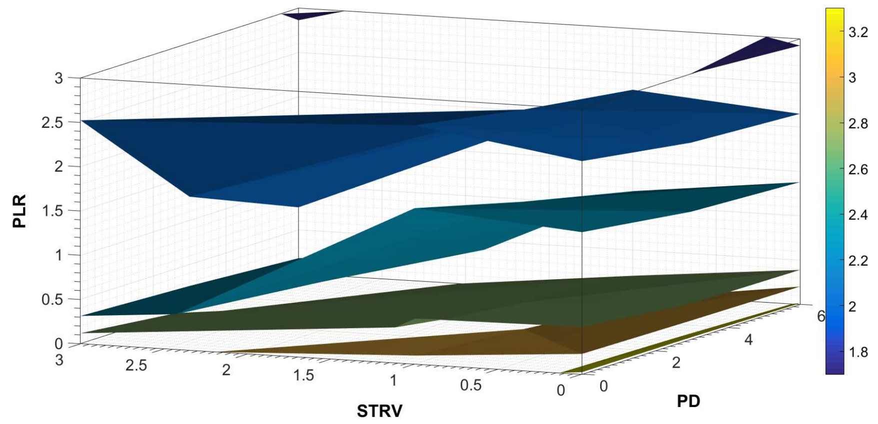

Figure 3.2: Isosurface graph for the video sequences coded at 200 kbps and rated on the Galaxy Tab. MOS values selected for the isosurface computation: 1.7, 2, 2.3, 2.7, 3, 3.3.

consist in a login page and a video section where the subjects can watch and rate the video sequences.

Eighteen individuals watched the videos with the Galaxy Tab while twenty-two used the iPad 2. The assessment was organized in sessions of 1.5 hours, during which each subject voted for a total of 45 minutes, alternating 15-minute voting intervals with 15-minute breaks. Three sessions were needed to complete the subjective assessment per subject, and one session was held every week. The video sequences were displayed in full-screen mode for both tablets. A rating page was automatically displayed after the end of each video playback. The voting period was not time-limited and after each vote the subjects had to confirm their choice. Upon confirmation, the next video page would be displayed. Such automatic procedure was iterated for all the 216 video sequences. The presentation order of the video sequences was randomized for each subject.

3.2.3 Results of the assessment

In order to graphically show the effects of the system IFs distorting the video sequences, isosurface figures at various MOS values were created. Figures 3.2 and 3.3 refer to the video sequences coded at 200 kbps and rated respectively on the Galaxy Tab and on the iPad 2 whereas Figures 3.4 and 3.5 refer to the video sequences coded at 400 kbps and rated respectively on the Galaxy Tab and on the iPad 2. In these graphs, each axis refers to one of the three considered parameters so that it is easy to analyze the impact of each parameter to the visual quality.

At first, it can be noted as for the isosurfaces representing fair to good quality levels ($4 \geq MOS > 3$), the PLR is mostly absent and only PD and STRV errors become relevant. The isosurfaces representing from poor to fair quality values ($3 \geq MOS > 2$) extend themselves on low PLR and multiple STRV errors. Finally, poor quality values ($2 \geq MOS > 1$) are

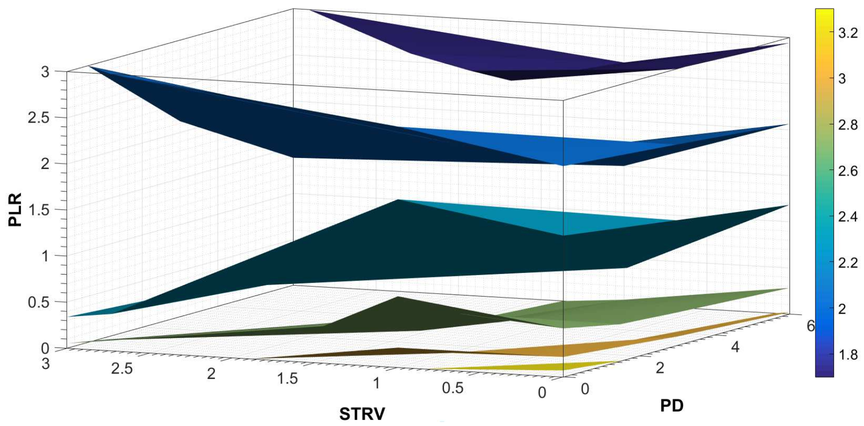

Figure 3.3: Isosurface graph for the video sequences coded at 200 kbps and rated on the iPad 2. MOS values selected for the isosurface computation: 1.7, 2, 2.3, 2.7, 3, 3.2.

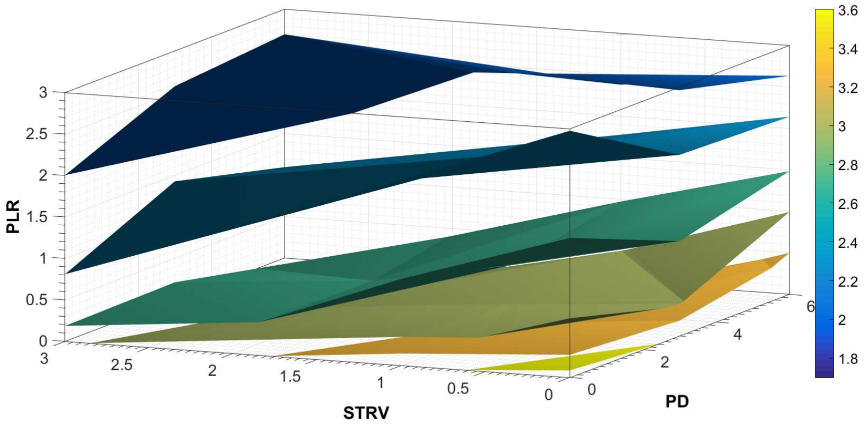

Figure 3.4: Isosurface graph for the video sequences coded at 400 kbps and rated on the Galaxy Tab. MOS values selected for the isosurface computation: 1.7, 2, 2.3, 2.7, 3, 3.3, 3.6.

characterized by high values of PLR and multiple STRV errors.

Furthermore, other important observations can be made:

- The PD in the range of considered values does not affect in a significant way the quality as perceived by the user of Internet videos on tablets. This can be observed by analyzing that the increase in the PD does not need to be compensated with the reduction of the other two distortion components to keep the same quality level. Accordingly, the starvation distortions could be avoided with a high playout delay to address periods of high network latency values.
- Low quality is observed mostly with high values of PLR. Indeed, on average, the PLR is the most annoying artifact. However, increases in the PLR can be compensate by guaranteeing the absence of starvations.

Whereas there are not significant differences in the shapes of the surfaces related to the two

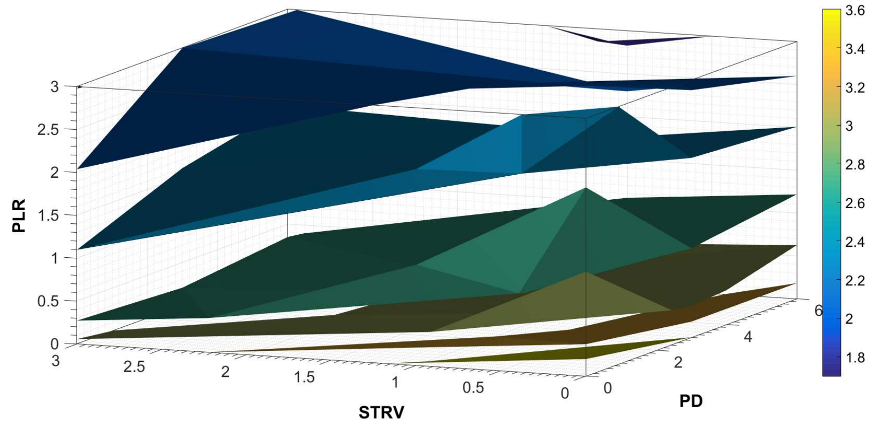

Figure 3.5: Isosurface graph for the video sequences coded at 400 kbps and rated on the iPad 2. MOS values selected for the isosurface computation: 1.7, 2, 2.3, 2.7, 3, 3.3, 3.6.

terminals, in general these graphs show that the iPad 2 provided the user with a better quality. This is prove that the perceived quality depends also on the used terminal. In brief, an initial buffering interval or a single starvation event appears more tolerable than multiple starvations or the occurrence of packet losses during the video playback. Even though the MOS results are very similar between the two tablet devices on equal terms of error conditions, it can be noted that for the video sequences coded at 400 kbps, the iPad 2 achieves a better performance when the PD is zero. These results can be explained by the overall faster iPad 2 interface, which increases the user expectation in terms of playback efficiency, which is dissatisfied when the PD is high.

3.2.4 Quality models

In order to define a QoE model able to evaluate the perceived quality, the suitability of a linear and nonlinear expression is investigated:

$$QI_l = a_{1l} \cdot Rate + a_{2l} \cdot PD + a_{3l} \cdot STRV + a_{4l} \cdot PLR + K_l \tag{3.1}$$

$$QI_{nl} = K_{nl} \cdot (a_{1nl})^{Rate} \cdot (a_{2nl})^{PD} \cdot (a_{3nl})^{STRV} \cdot (a_{4nl})^{PLR} \tag{3.2}$$

Table 3.3 shows the values of the coefficients obtained by computing the linear and the nonlinear (logarithmic) regression between the considered impairments and the MOS values rated on the iPad 2, the Galaxy Tab and their average. By considering the linear quality model, QI_l, and the nonlinear quality model, QI_{nl}, the values of the coefficients are very similar for both devices, except for a_{2l}, whose value is almost twice for the iPad 2 with respect to the Galaxy Tab. This confirms that the annoyance generated by the playout delay error is greater in the iPad 2 with respect to the Galaxy Tab.

Table 3.3: Values of the coefficients for both the linear and the nonlinear regression in Eqs. (3.1) and (3.2).

Coefficient	MOS iPad 2	MOS Galaxy Tab	Average MOS
a_{1l}	0.00150	0.00096	0.00123
a_{2l}	-0.03767	-0.02045	-0.02906
a_{3l}	-0.13384	-0.15625	-0.14504
a_{4l}	-0.36291	-0.38200	-0.37246
K_l	2.80587	2.99891	2.90239
a_{1nl}	1.00055	1.00036	1.00045
a_{2nl}	0.98638	0.99181	0.98918
a_{3nl}	0.95375	0.94634	0.95005
a_{4nl}	0.85786	0.85324	0.85566
K_{nl}	2.76619	2.96463	2.86692

Table 3.4: Pearson correlation values computed between the proposed quality models and the MOS results.

Quality model	MOS iPad 2	MOS Galaxy Tab	Average MOS
QI_l with iPad 2 coefficients	0.841	0.848	0.860
QI_{nl} with iPad 2 coefficients	0.857	0.863	0.876
QI_l with Galaxy Tab coefficients	0.833	0.857	0.860
QI_{nl} with Galaxy Tab coefficients	0.850	0.872	0.877
QI_l with average coefficients	0.839	0.855	0.862
QI_{nl} with average coefficients	0.855	0.870	0.878

Table 3.4 summarizes the Pearson correlation values between the proposed quality models and the MOS results. Given the strong correlation between the MOS values and the quality models, these could be used in a video streaming transmission system to estimate the quality perceived at the receiver side by estimating or measuring the values of the distortion parameters affecting the video transmission.

3.3 QoE perception when streaming videos: the impact of interactivity

In this Section, the influence of interactivity on the QoE perceived when streaming video on tablet devices is analyzed. The aim is to go further in the analysis of the importance of the interactivity by conducting subjective assessment tests aimed at isolating the contribution of the relevant features on the final QoE with respect to other impacting factors and specifically to system IFs considered in Section 3.2. In the literature, there is not a standard definition of interactivity. Therefore, in this thesis it is assumed that the interactivity in multimedia services concerns the control of an application such as take decisions on the main contents and activate extra contents (contents enriching the main application content). Interactivity is an important element that affects the overall QoE, which may even mask the impact of the quality level of the (audio and visual) signal itself on the overall user perception.

In order to investigate the influence of the interactivity on the perceived video quality, two types of video consumption experiences have been implemented: plain single video sequence and video playlist with interactive features. In addition, each of the video consumption experiences has been implemented in two versions: with and without the inclusion of buffer starvation errors, for a total of 16 video consumption experiences whose quality have been rated by 25 subjects. Finally, the contributes to the QoE perception provided by system and interactivity IFs are combined for the estimation of the overall QoE so as to investigate whether the layered model proposed in Section 3.1 is valid.

3.3.1 Test video sequences

Four video categories have been considered, namely *Cartoon*, *Documentary*, *Technology* and *How it's made*. For each video category four different video sequences have been selected and two types of video consumption experiences have been organized: plain Single Video sequence (SV) and Video Playlist with interactive features (VP). While in the SV experience the user is asked to watch a unique video sequence with no possibility of interaction, in the VP experience the user is allowed to pick a video from a playlist, and to move from a video to the others without constraints. Furthermore, the user is allowed to jump forward, backward, pause and resume each video during the playback at any time. In addition, English subtitles can also be turned on/off for videos with English audio, and a text box is superimposed every 30s advertising the other videos available from the playlist.

For the SV experience, a single three-minute-long video sequence is displayed, chosen among the four videos selected for each category. Conversely, for the VP experience, all four video sequences belonging to the same video category are made available to the user in a video playlist, where each video is 4:30 minute long. The user is allowed to watch and browse the videos belonging to the same category for a total length of 4:30 minutes. The encoding parameters of the video sequences are summarized in Table 3.5. Figures 3.6, 3.7 and 3.8 show three snapshots of the SV and VP experiences.

In addition, each of the eight video consumption experiences has been implemented in two versions: with and without the inclusion of buffer starvation errors. The buffer starvation causes

Table 3.5: Video and audio encoding parameters for the selected video sequences.

Video	Resolution	1024×600 pixels
	Bitrate	2.5 Mbps
	Codec	H.264 - MPEG-4 AVC (part 10)
	Decoded format	Planar 4:2:0 YUV
Audio	Bitrate	160 kbps
	Codec	MPEG AAC
	Sampling	48 kHz
	Channels	Stereo

Figure 3.6: Snapshot of the SV experience.

an interruption in the playback, which is, in general, partially masked by the decoder by freezing the video to the last decoded frame and interrupting the audio. These events are inserted each 20 s in all the corrupted video sequences and last for 1 s, with a total of 9 starvation occurrences for SV and 13 starvation occurrences for each video of the VP. These events simulate the condition of playback buffer underflows determined by peaks in the network latencies. The intention is to evaluate the impact of the interactivity varying other parameters of the video streaming scenario.

A dedicated wireless LAN has been used for the video streaming so that no additional impairments are introduced. Indeed, all the configurations discussed above have been simulated so as to have a complete control of the assessment environment. With such *ideal* wireless channel, the artefacts visible in the decoded video sequences should only depend on the streaming simulation process previously described. Then, the distortion parameters can be controlled so to achieve more specific results in the subjective assessment.

Figure 3.7: Snapshot of the VP experience. On the bottom, the user can choose the video to watch from the playlist.

Figure 3.8: Snapshot of the VP experience showing the subtitles and a text box (in Italian) advertising another video from the same playlist.

3.3.2 Subjective evaluation procedure

For evaluating the QoE, a subjective assessment has been conducted involving 25 subjects which were asked to rate the 16 video consumption experiences. For subjective tests, the specifications given in [34] have been adopted. Specifically, the single-stimulus Absolute Category Rating (ACR) method has been adopted, which consists in presenting the test sequences one at a time and allowing for their independent evaluation on a category scale. The following five-level ITU scale for rating overall quality has been used: 5 stars (Excellent), 4 stars (Good), 3 stars (Fair), 2 stars (Poor), 1 star (Bad). The scores assigned by the observers have been averaged in order to obtain the Mean Opinion Score (MOS).

The tablet employed by the subjects for watching the video sequences was a BlackBerry PlayBook, whose technical specifications are:

- display: 7″ diagonal, 1024×600 resolution, LCD
- operating system: BlackBerry PlayBook OS 2.1.0.1526
- web browsing: Adobe Flash 11.2 enabled, built-in support for HTML5

A website has been implemented for the display of the video sequences and the scoring procedure. The website consists in a login page for the user authentication and in video pages where the subjects can watch and rate the video sequences. The video pages are based on an embedded video player manageable using JavaScript, which has been used to play the video sequences previously uploaded to a local server The assessment started with a pre-test phase, during which the user was provided with short written instructions and with a brief detailed oral explanation: purposes of the study, types of video consumption experiences and rating scale details were also presented. Furthermore, during this phase the users were asked to rate a set of training video sequences which introduced the users to the types of video consumption experiences and to the interactive features available during the video consumption.

The assessment has been carried out in two 45-minute sessions, held in two different days. The video sequences were displayed in full-screen mode while each subject was wearing earphones. A rating page was automatically displayed after the end of each single video playback in the case of SV experience, and after 4:30 minutes from the start of the first video playback in the case of VP experience. On the rating page each subject had to select a discrete value between 1 and 5 indicating the overall quality of the video experience just consumed. The voting phase was not time-limited and after each vote the subjects were asked to confirm their choice. Upon confirmation, the next video experience would be activated. Such automatic procedure was iterated for all the 16 video experiences. The presentation order of the video experiences has been randomized for each subject.

3.3.3 Results of the assessment

MOS values with 95% confidence interval (CI) have been computed for each video consumption experience from the analysis of the experimental data. Figure 3.9 shows the MOS results for the SV and VP consumption experiences computed for each of the four video categories, and their average, with (WS) and without (NS) starvation. As expected, the results show that the video experiences distorted by starvation errors achieved lower quality values than the *clean* video experiences. Moreover, the negative impact of the starvation errors on the perceived quality is much higher (-32.39%) than that of the absence of interactivity (-10.91%). However, VP experiences achieved higher quality values than SV experiences. Indeed, VP provides an increase of

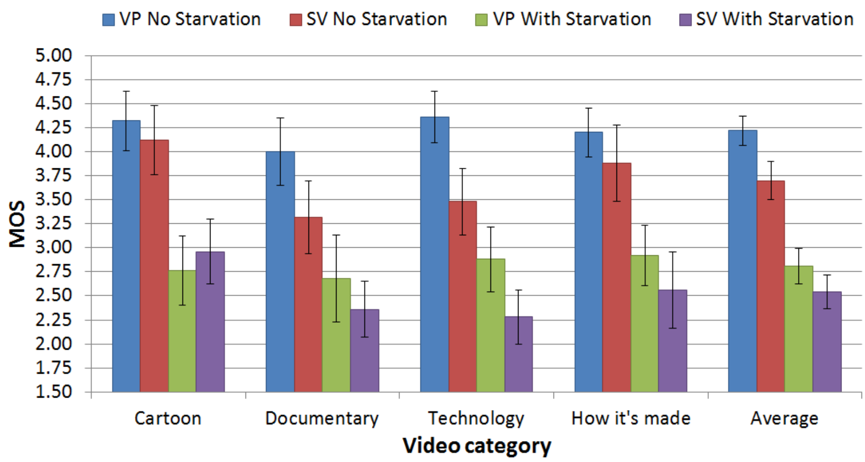

Figure 3.9: MOS results with 95% CI for the SV and VP consumption experiences computed for each of the four video categories, and their average, with (WS) and without (NS) starvation.

the perceived quality respect to SV on both NS and WS cases with comparable results: +12.36% for NS and +9.46% for WS. From these results, the interactivity can be considered as an additive parameter able to increase the overall quality of the video experiences.

As a prove of the fact that the starvation errors have a greater negative impact on the perceived quality than the absence of interactivity, from the average MOS in Figure 3.9 it can be noted that while for the video sequences WS the difference of perceived quality between SV and VP is less relevant (MOS increases from 2.54 to 2.81, which correspond to poor quality in both cases), for the video sequences NS the MOS increases from fair (SV: 3.7) to good quality (VP: 4.22). This confirms that although interactivity has a good impact on perceived quality, it can be represented by an additive component only partially. Indeed, the presence of starvation implies a quality degradation which is difficult to compensate even with the addition of interactivity features.

Regarding the video categories, it can be noted that for the categories Cartoon and How it's made the MOS difference between SV and VP is not as evident as for the categories Documentary and Technology. This aspect highlights the fact that the introduced interactivity is more interesting when linked to a video that is *teaching* us something; having more information with these functionalities make the service more attractive.

In order to understand how interactivity influences the QoE, several dedicated parameters have been recorded in the case of VP experiences. The results show that, on average, each subject watched at least two video sequences out of four. Furthermore, the average time spent watching the main video sequence (the first video of each VP, which is the same video shown in the SV experience) is essentially equal to the average time spent watching one of the other three video sequences. Finally, the correlation between the given suggestions (a text box is displayed every 30 s advertising the other videos) and the user choices to watch the advertised videos has been investigated. As a result, the subjects only chose to watch an advertised video sequence in the 3.78% of times

3.3.4 Quality models

The linear and nonlinear QoE models defined in Section 3.2.4 are able to evaluate the quality perceived by the user when videos are distorted by some system IFs, namely the source coding bitrate (Rate), the playout delay (PD), the starvation (STRV) and the packet loss rate (PLR). Firstly, these models are validated in the proposed video streaming scenario. Accordingly, the expressions described in Eqs. (3.1) and (3.2) have been modified by considering only the bitrate and the starvation parameters, as follows:

$$QI_l = a_{1l} \cdot Rate + a_{3l} \cdot STRV + K_l \tag{3.3}$$

$$QI_{nl} = K_{nl} \cdot (a_{1nl})^{Rate} \cdot (a_{3nl})^{STRV} \tag{3.4}$$

The values of the coefficients are reported in Table 3.3. A correlation value of 0.842 and 0.862 is achieved between the MOS from the proposed work and the quality models expressed in Eqs. (3.3) and (3.4), respectively. The achieved correlation values are good, considering that the interactivity is not taken into account yet.

With regard to the layered model proposed in Section 3.1, system IFs (bitrate and starvation) are considered by the Components layer. The Combination layer accounts for the mathematical functions used to estimate the multimedia quality. Finally, the Control layer accounts for the influence of interactivity. In order to take into account the interactivity feature, Eqs. (3.3) and (3.4) have been further modified by including the interactivity in both additive and multiplicative forms, as follows:

$$QI_l^a = [a_{1l} \cdot Rate + a_{3l} \cdot STRV + K_l] + a_{5l}^a \cdot KI_l^a \tag{3.5}$$

$$QI_{nl}^a = [K_{nl} \cdot (a_{1nl})^{Rate} \cdot (a_{3nl})^{STRV}] + a_{5nl}^a \cdot KI_{nl}^a \tag{3.6}$$

$$QI_l^m = [a_{1l} \cdot Rate + a_{3l} \cdot STRV + K_l] \cdot a_{5l}^m \cdot KI_l^m \tag{3.7}$$

$$QI_{nl}^m = [K_{nl} \cdot (a_{1nl})^{Rate} \cdot (a_{3nl})^{STRV}] \cdot a_{5nl}^m \cdot KI_{nl}^m \tag{3.8}$$

Table 3.6: Pearson correlation values computed between the MOS_V and the QoE models defined in Eqs. (3.5)-(3.8).

Quality model	QI_l^a	QI_{nl}^a	QI_l^m	QI_{nl}^m
Pearson correlation	0.939	0.941	0.933	0.933

The subjective ratings have been divided in two datasets: a training dataset composed of the ratings provided by the first 15 subjects and a validation dataset composed of the ratings provided by the last 10 subjects. MOS_T and MOS_V values were computed respectively from the training and validation datasets. Thereafter, by computing a regression between the considered impairments and the MOS_T values, the following coefficients have been obtained: $KI_l^a = 0.790$, $KI_{nl}^a = 1.683$, $KI_l^m = 1.160$ and $KI_{nl}^m = 1.256$. The coefficients a_{5l}^a, a_{5nl}^a, a_{5l}^m, and a_{5nl}^m, take into account the presence of interactivity, then their value is equal to 1 if the video sequences with interactivity is evaluated, while for the video sequences without interactivity $a_{5l}^a = a_{5nl}^a = 0$, $a_{5l}^m = 1/KI_l^m$, and $a_{5nl}^m = 1/KI_{nl}^m$. Afterwards, the Pearson correlation values achieved between the MOS_V values and the quality models defined in Eqs. (3.5)-(3.8) have been computed and are summarized in Table 3.6.

Therefore, the results demonstrate that the interactivity feature can be successfully translated into both an additive or multiplicative parameter in existing quality metrics. Then, the influence of the interactivity on the video quality can be considered separately from the influence of the coding and transmission parameters. This means that IFs belonging to different layers can be firstly considered independently and then be combined for estimating the overall QoE. Accordingly, these results validate the layered model proposed in Section 3.1. However, this study is considered preliminary as interactivity involves a complex and heterogeneous set of features which can only be partially modelled through the features introduced in these experiments. Moreover, the influence of more IFs belonging to different layers should be considered and evaluated independently and then combined for estimating the overall QoE in order to further validate the proposed layered approach. For this reason additional investigation is needed to confirm the obtained results.

3.4 QoE perception when streaming videos: the impact of device switching

The objective of this study is to understand the influence of the device on the quality perceived by users watching video contents. Specifically, the influence of device switching is investigated. Device switching means that the user starts watching a video sequence on a device, and at a specific moment (called switching time), the video is streamed on a different device in which the user continues watching the video. This scenario can happen, for example, when the user starts watching a movie on her TV and, being uncomfortable, she moves to his bedroom where she continues watching the movie on the tablet. Another example may be a user which starts to watch a movie to her home on the TV; then, the user has to leave her home and continues watching the movie on her mobile device (tablet, smartphone, laptop) by using a mobile Internet connection. In this case, the capacity of the mobile service has to be taken into account, too. Many other scenarios can be imagined in which a user for any reason decides to switch the device on which is playing back the video.

The scenario specifically considered in this study is represented by a user owning two different devices: a TV as home and fixed device, and a tablet as mobile device. The choice of such scenario aims at demonstrating that the QoE is not only related to the video consumption on the single device, but it takes into consideration the overall experience of watching the whole video by switching between different devices; for this reason, two devices with very different characteristics and technical capabilities were deliberately chosen, i.e., a TV screen (52″) and a tablet (9.7″).

Furthermore, two different viewing modes are considered:

- Single Device Viewing (SDV) mode: the user watches the entire video with the same device, either TV or tablet.
- Multi-Device Viewing (MDV) mode: the user begins to watch the video on the TV then switches to the tablet at the switching time.

In order to investigate the influence of device switching on the perceived video quality, 18 test conditions (TCs) were selected by varying the parameters considered for conducting the assessment: the viewing modes, the devices and the video qualities. Then, 28 subjects rated the quality of the video sequences for the 18 TCs.

3.4.1 Test video sequences

Four open-source video contents have been encoded with FFMPEG [117] at three quality levels, identified with Q_1, Q_2 and Q_3, which correspond to the pairs (4500 kbps, 1920×800), (2000 kbps, 1104×506), and (900 kbps, 624×286). In fact, video resolution is often scaled accordingly with video bitrate since encoding the same resolution at inappropriately low bitrates introduces objectionable compression side effects into the video such as blockiness, twirling details, color smearing, etc. By lowering the resolution proportionally to the bitrate, a consistent level of compression quality is maintained at the expenses of removing some content details [118].

Table 3.7: Video and audio encoding parameters for the selected video sequences.

Video	Bitrate and resolution	4500 kbps - 1920×1080 pixels (Q_1)
		2000 kbps - 1104×506 pixels (Q_2)
		900 kbps - 624×86 pixels (Q_3)
	Scaled resolution	1920×1080
	Codec	H.264 - high profile, MPEG-4 AVC (part10)
	Decoded format	Planar 4:3:0 YUV
	Frame rate	24 fps
	GOP size	2 s (48 frames)
Audio	Bitrate	320 kbps
	Codec	MPEG AAC
	Sampling	48 kHz
	Channels	Stereo

Only video quality changes were introduced, while audio quality was kept the same for all the contents. Audio and video encoding details are summarized in Table 3.7.

Afterwards, excerpts of approximately three-minute-long video sequences were selected from each source video content previously encoded, for a total of 18 Source Reference Circuits (SRCs). The borders of the excerpts of each video were selected so that they are aligned with logical scenes and that an interesting scene is not interrupted in the middle. Eighteen test conditions (TCs) were selected by varying the parameters considered for conducting the assessment: the viewing modes, the devices and the video qualities. TCs are summarized in Table 3.8.

During the assessment, TCs were paired randomly with SRCs. Each TC-SRC pair is identified as a Processed Video Sequence (PVS). For each user, the following rules have been defined:

- SRCs and TCs are paired randomly;
- each TC is presented only one time;
- each SRC is presented only one time;
- two consecutive PVSs have SRCs coming from different video contents;
- PVSs are presented in random order.

The HTTP Adaptive Streaming (HAS) has been considered for video streaming, i.e., a technique which consists in segmenting a video into few second long intervals and encoding these segments in multiple quality versions. The higher the segment bitrate, the higher its resulting quality. The SRCs have been streamed at different quality levels and HAS-typical changes from one level to another have been introduced during the same streaming session. For the conditions involving device switching, it has been timed to happen together with a quality

Table 3.8: Test Conditions (TCs).

TC	Viewing mode	Device	Video quality
0	SDV	TV	Q_1
1	SDV	TV	$Q_1 \rightarrow Q_2$
2	SDV	TV	$Q_1 \rightarrow Q_3$
3	SDV	TV	Q_2
4	SDV	TV	$Q_2 \rightarrow Q_3$
5	SDV	TV	Q_3
6	SDV	Tablet	Q_1
7	SDV	Tablet	$Q_1 \rightarrow Q_2$
8	SDV	Tablet	$Q_1 \rightarrow Q_3$
9	SDV	Tablet	Q_2
10	SDV	Tablet	$Q_2 \rightarrow Q_3$
11	SDV	Tablet	Q_3
12	MDV	TV $\rightarrow$ Tablet	$Q_1 \rightarrow Q_1$
13	MDV	TV $\rightarrow$ Tablet	$Q_1 \rightarrow Q_2$
14	MDV	TV $\rightarrow$ Tablet	$Q_1 \rightarrow Q_3$
15	MDV	TV $\rightarrow$ Tablet	$Q_2 \rightarrow Q_2$
16	MDV	TV $\rightarrow$ Tablet	$Q_2 \rightarrow Q_3$
17	MDV	TV $\rightarrow$ Tablet	$Q_3 \rightarrow Q_3$

switching event, simulating the realistic case of *taking the session with the user* on a different device. Only one value of switching time has been chosen, which is placed at the middle of the video sequence. However, the switching time may vary from content to content in order to avoid switching on a captivating or busy/action scene that would be annoying for the user. In fact, video quality variations are more noticeable in a steady or tracking scene, especially when the mind can predict what should be next in the scene [119].

The simulation of the HAS technique imposes the need to concatenate video streams of different video quality (in terms of bitrate and resolution) to obtain videos with variable quality. For this reason, SRCs were all scaled up to the same *native* resolution (1920×1080) with FFMPEG to make the concatenation possible. Scaling was also applied to video sequences with constant quality. Video concatenation was done in correspondence with Group-of-Picture (GoP) boundaries at IDR-frames in order to realize a smooth video quality transition (a GoP of 2 s is chosen, which fits with that used by commercial HAS video players as Adobe HTTP Dynamic Streaming and Microsoft HTTP Smooth Streaming). The scaling method is the same used by video players that automatically scale video contents to full screen.

In order to simulate a HAS configuration, a testbed composed of a server, a PC, a wire-

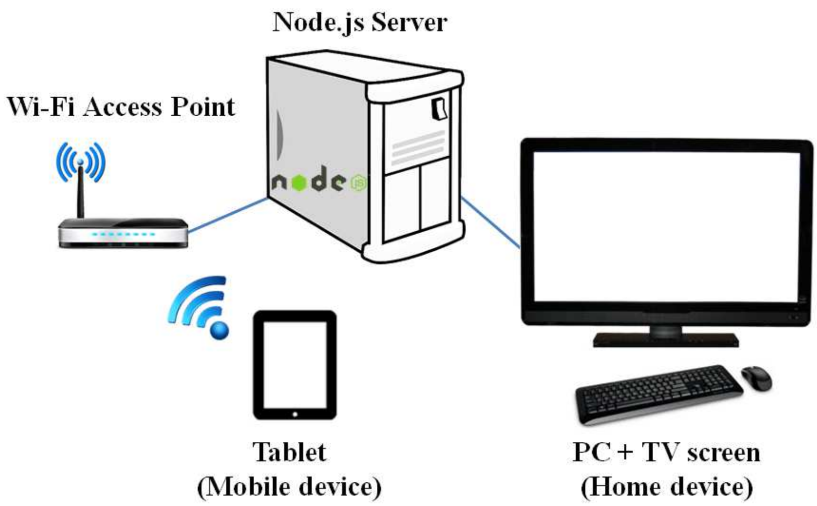

Figure 3.10: Testbed configuration.

less network, and the two devices (the TV screen and the tablet) has been implemented, as shown in Figure 3.10. The server runs on the PC and its main task is to allow the synchronization of the devices on the correct video sequence and at the correct seek position during the device switching. Node.js [120] and WebSocket [121] protocols have been used to implement the server. Socket.IO plugin [122] has also been installed to improve and simplify the usage of WebSocket. This protocol has been chosen in order to have the most *realtime* communication possible.

To avoid undesirable playout delays, the video sequences were not streamed over the network, but were stored locally in both the hard disk of the PC and the flash memory of the tablet. The videos stored on the PC were displayed on the TV screen through HDMI, while those stored on the tablet's memory were displayed on the tablet screen. A Wi-Fi access point creates a local ad-hoc Wi-Fi network inside the test room to establish communication between the server and the devices. The server (the PC) is connected to the access point by ethernet cable. The TV screen application is a web app running on the Chrome browser installed on the PC; a web application was also developed for the tablet. The two applications have quite the same capabilities: they download the file containing the pre-defined random TC-SRC pairs list of the current user, and play the video sequences following this order. Furthermore, they are able to make TV and tablet communicate each other through the server, over the Wi-Fi network. The server acts like a man-in-the-middle device: it re-routes the information exchanged back-and-forth between the two end-devices.

3.4.2 Subjective evaluation procedure

A subjective quality assessment was conducted involving 28 subjects which were asked to rate the quality of the 18 video experiences. The assessment started with a pre-test phase, during which the user was provided with short written instructions and with a brief detailed oral explanation: purposes of the study, viewing modes and rating scale details were also presented. Following ITU-T guidelines [34], the visual acuity of the subjects was tested [123]. Afterwards, the user sat in front of the TV screen at a distance of 2 m, and she was allowed to set her favorite room illumination. Furthermore, she was provided with the tablet, and with a mouse to control the TV. Before conducting the assessment, some test video sequences were displayed in order to give each user an overview of the video sources, the viewing modes and the video qualities involved in the experiment.

The technical specifications of the devices employed for assessment are:

1. Apple iPad 2
    - display: 9.7″ diagonal, 1024×768 resolution, 132 PPI
    - operating system: iOS 5.0.1
    - browser: Safari.
2. TV screen, connected through HDMI to PC
    - display: 52″ diagonal, 1920×1080 resolution, LCD
    - operating system: Windows 7
    - PC browser: Google Chrome

The video assessment (test phase) consisted of a viewing of 18 three-minute long video sequences. Videos were played in full screen mode both on the TV screen and on the tablet. Special attention has been given to the end user interface, in order to create a user friendly application. In fact, the application guides the user through the video playing, device switching, video rating and feedback phases, with simple and intuitive buttons/indications. The device switching is real-time: when the video playback ends on the TV, a *Play* button is immediately shown on the tablet, and the user can manually restart the video playback when she is ready to watch. At the end of each video sequence, the interface shows the rating form where the user is asked to insert his rate for the video just shown. Then, the next video sequence is played with the same procedure till the end of the test.

The users were allowed to take a break of 5 min after the ninth sequence (half duration of the test). The overall test duration was about 1 hour and 15 min, during which the user watched about 50 min of videos. The single-stimulus Absolute Category Rating (ACR) method has been adopted, which consists in presenting the test sequences one at a time and allowing for their

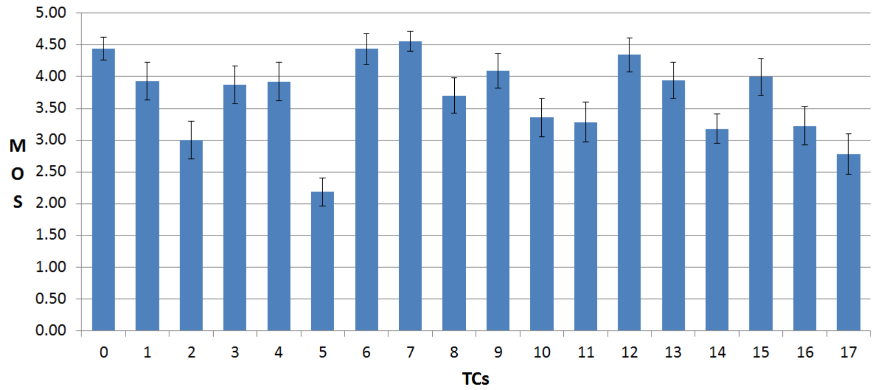

Figure 3.11: MOS values with 95% confidence interval for the 18 TCs.

independent evaluation on a category scale. The method specifies that after each presentation the subjects must be asked to evaluate the quality of the sequence just shown. The following five-level ITU scale for rating overall quality has been used: 5 stars (Excellent), 4 stars (Good), 3 stars (Fair), 2 stars (Poor), 1 star (Bad). The user always gave one rate per video sequence, also for test conditions involving MDV: the rate expresses the overall video quality perceived by the user for the whole sequence on both the devices. The scores assigned by the observers have been averaged in order to obtain the Mean Opinion Score (MOS).

3.4.3 Results of the assessment

The MOS have been computed from subjective results for each TC, together with the 95% confidence interval. The results are shown in Figure 3.11. In the following, MOS results are analyzed focusing on TCs regarding different viewing modes, video with constant quality, video quality switching, and device switching.

Device dependency

The first analysis concerns the viewing mode which can be SDV and MDV. TCs involve the displaying of the videos on a single device (a TV screen or a tablet) and on both devices. In both cases the only variable is video quality, which can be constant or can change. Figure 3.12 compares MOS values as a function of video quality for each viewing mode. With regard to the TV screen, MOS values show that users prefer lower but constant video quality (TC_3) and smooth decreasing video quality (TC_1, TC_4) than abrupt decreasing video quality (TC_2). However, it is evident that the user noticed the case of too low video quality on the TV screen (TC_5). With regard to the tablet device, except for TC_{10}, MOS values are higher than those concerning the TV screen. On the tablet, low video qualities are perceived as better by the users, probably because impairments are less noticeable on the tablet due to the smaller screen

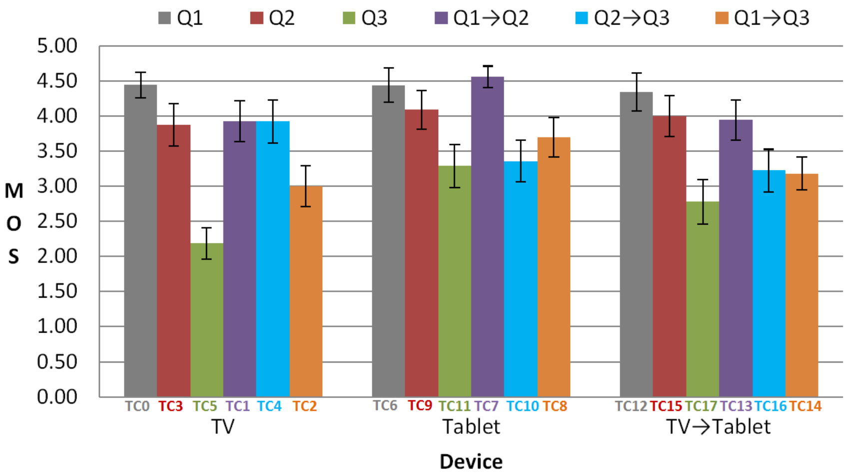

Figure 3.12: MOS values as a function of video quality for each viewing mode.

size with lower resolution. In fact, high to medium video quality switching (TC_7) obtained a MOS even higher than the highest video constant quality (TC_6), probably because the quality difference between the highest and the medium video quality is more difficult to notice on the tablet. TCs with lower video quality obtained the lowest MOS values. MDV TCs involved the displaying of the video on both the devices: the playback starts on the TV screen, then at the switching time the video is streamed on the tablet. The only variable is video quality, which can be constant or can change at the switching time. As for SDV, TCs with the lowest video quality obtained the lowest MOS values, included TCs involving video quality switching.

Constant video quality

Figure 3.13 compares MOS values for videos with constant video quality among the different viewing modes. For both viewing modes, MOS values decrease along with video quality. Except for the highest video quality which obtained similar MOS values for all viewing modes, MOS values are higher on the tablet and lower on the TV. This confirms that low video qualities are perceived as better on the tablet than on the TV (due to the smaller screen and lower resolution of the tablet). MOS values for TCs with constant video quality (TC_{12}, TC_{15}, TC_{17}) decrease when compared to the tablet-viewing case, especially for TC_{17} with lowest video quality. An interesting result is that MOS values for MDV are about the average between the MOS values obtained on the TV and on the tablet. Users' comments reveal important and peculiar aspects about this condition: many users perceived an increase of the quality when switching from the TV screen to the tablet, although the quality was kept constant.

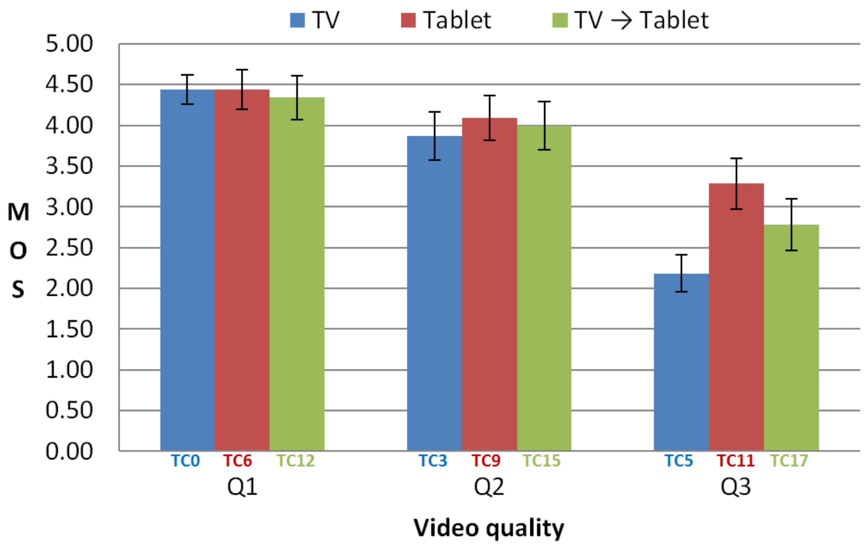

Figure 3.13: MOS values for videos with constant video quality among the different viewing modes.

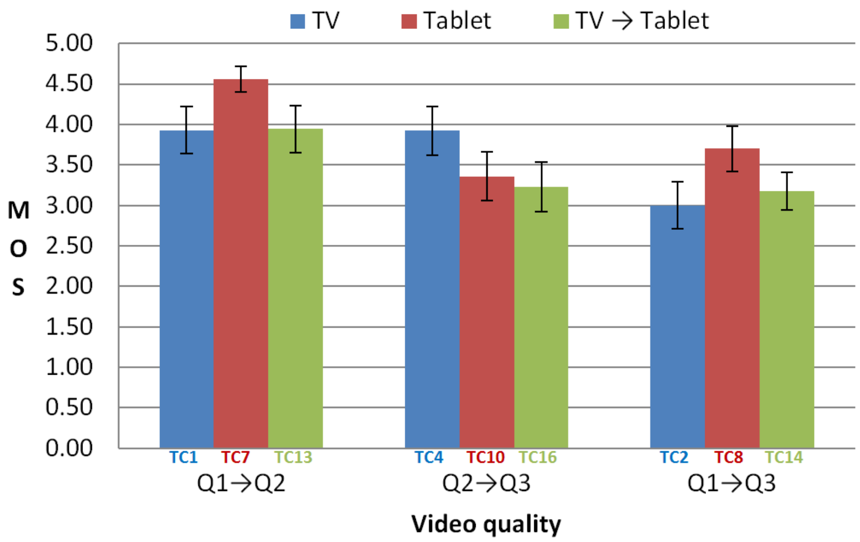

Figure 3.14: MOS values for video quality switching TCs among the different viewing modes.

Video quality switching

Figure 3.14 compares MOS values for video quality switching TCs among the different viewing modes. Switching from the highest to the medium video quality resulted in the same MOS value for TV SDV and MDV, while for tablet SDV a higher MOS value has been obtained. Switching from the highest to the lowest video quality resulted in a low MOS value for TV SDV, a slightly (but not significantly) higher MOS value for MDV and the highest MOS value for tablet SDV. When switching from the medium to the lowest video quality, the results between tablet and switching from TV to tablet are comparable. However, quality has been rated significantly higher for the TV-case. This is surprising, and may be due to the lower expectation when starting from an already low quality level. This case will require further study, however.

Finally, the following conclusions are reached: low video qualities achieve higher MOS values when the viewing device is a tablet rather than a TV screen; similarly, many users perceived a slight increase in the quality when switching from the TV screen to the tablet, even in the case the quality is kept constant, without a strong effect on the MOS ratings, however. QoE for video quality switching is in line with the average MOS for the constant quality scenario at the considered quality levels. Nevertheless, in this case a QoE model has not been defined because this scenario is too specific. Indeed, the reverse scenario of device switching from a tablet to the TV, and the consideration of additional devices, such as smartphones and laptops, are subjects of future works.

3.5 QoE in the Multimedia Internet of Things

In this Section, a first approach on QoE modelling for the Internet of Things (IoT) is discussed. The IoT is a world-wide network of interconnected objects, uniquely addressable, based on standard communication protocols [53]. Since its conception at the beginning of last decade, it has evolved by incorporating more and more technologies so that different types of devices are part of it: from RFID tags to sensors, from simple actuators to complex wireless sensors networks, from connected cars to wearables and multimedia devices. With all of these kinds of objects, IoT covers many different domains of utilization, and several applications exist with heterogeneous requirements and purposes.

Size, heterogeneity, the criticalness of the envisioned applications and the limitations of the resources of the components make the IoT a very complex environment, rich with opportunities and threats. It is unlikely that even the most advanced of the IoT devices will be able to survive and operate effectively in such a context, individually. IoT platforms have then the objective to combine and control the flows of traffic and signals received from different objects, processing in real time and offline the data and take actions, which will impact at the end (hopefully in a positive way) the quality of life of the humans.

In this scenario, the evaluation of the performance of IoT applications is becoming more and more important as relevant deployments are ubiquitously present in our everyday life activities. However, the plethora of IoT applications is quite vast, so that giving some guidelines on how to conduct this evaluation is very complex in a fast changing setting. Some studies related to this issue have been conducted with reference to the QoS evaluation models for IoT applications [58, 59]. However, there are only a few efforts in the direction of evaluating the QoE [67, 68]. Being user-centric, the QoE provides a more holistic understanding of the system's influence factors with respect to the technology-centric measures of the QoS approach.

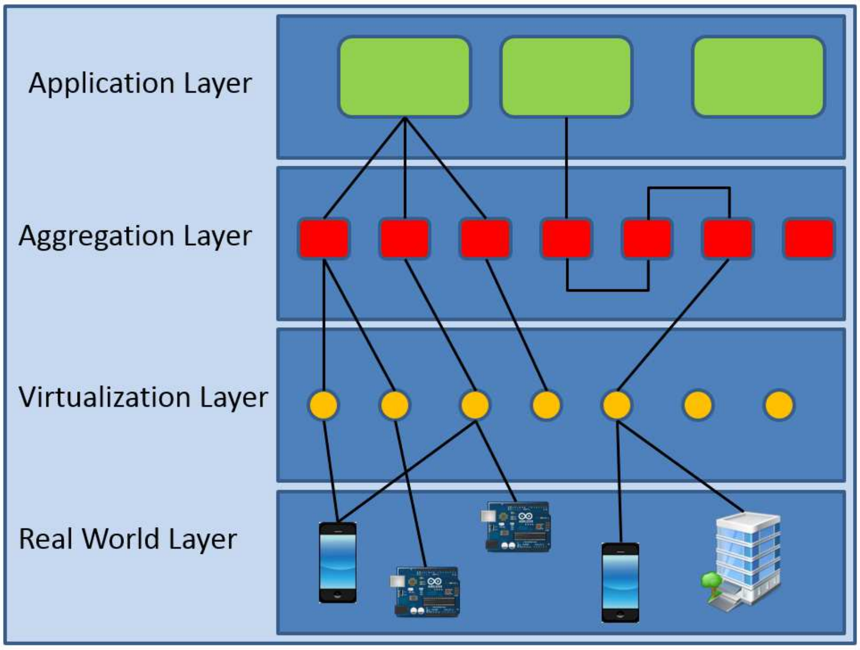

Figure 3.15: The considered four-layer model for IoT architectures.

The objective of this study is to analyze a reference IoT architecture to provide guidelines on which influence factors should be considered and measured for the evaluation and management of the QoE in different application scenarios. Then, the concept of Multimedia IoT (MIoT) is introduced in order to focus on the applications in which people are involved as the end-users of the multimedia content provided by the MIoT applications. On the basis of this analysis, a QoE management framework is proposed aimed at evaluating and controlling the contributions of each influence factor to estimate the overall QoE of MIoT applications. Finally, as a practical use case, a vehicular MIoT application has been implemented and used to conduct a subjective quality assessment to verify the applicability of the proposed approach.

3.5.1 Reference IoT architecture

The current IoT generation is mostly developed around the association of a virtual object (VO) to each physical object. The VO has the role of virtualizing the functionalities of the physical object, which is then part of the IoT. Furthermore, the storage of the data and running of the application have been moved to the cloud. As discussed in Section 2.1.2, there is not a reference IoT architecture yet. However, a general four-layer model whose major feature is the use of the VO is illustrated in Figure 3.15 and regards the architecture of the Lysis platform [66]. This solution is based on the iCore architecture [65], and exploits and leverages the adaptation capabilities offered by the platform in terms of virtualization, aggregation and abstraction properties.

The following are the functionalities of the different layers:

- **Real-world layer**: refers to the Real-World Objects (RWOs), i.e., the physical sensing devices that acquire the information that will be used by the IoT application;
- **Virtualization layer**: creates the VOs, which virtualize the functionalities of the associated RWOs;
- **Aggregation layer**: different VOs can be combined in order to create Composite Virtual Objects (CVOs) capable of providing a determined service that a single VO cannot accomplish;
- **Application layer**: plans and understands what requested services are needed by the IoT application. As such, it determines the strictly needed Service Level Agreement (SLA) that the platform is to execute by means of its CVO (and VO); this layer also exports all of the system's functionalities to the final user.

With regard to quality assurance, this architecture considers an SLA assurance function at the CVO level. Based on available policies, this function may observe if the matching CVO for a certain service execution request is deployable and executable based on the current and predicted availability of resources for SLA fulfillment. However, a module for evaluating the final quality provided to the end-user of the IoT application is not considered.

3.5.2 The Multimedia Internet of Things

As discussed in Section 2.1.1, the QoE is defined as *"the degree of delight or annoyance of the user of an application or service."* [6]. Such a definition of QoE is valid for general multimedia applications and services; therefore, it can also be extended to IoT applications. A huge number of IoT applications has been developed for different domains of utilization such as healthcare, smart home, smart city, smart grid, smart environment, transportation, security and surveillance. However, not for all IoT applications is the QoE management of interest, as the user is not always the recipient of the services. Indeed, if the application output is received by another system, then the performance of the application can be evaluated through a classical QoS-based approach. In fact, the objective of the QoE management activity is to have the whole control of the delivered service as perceived by the end-user to optimize the quality while controlling the utilized resources of each system component (in the IoT platform for the interest of this work). Additionally, the focus is on the evaluation of the QoE for applications where the multimedia content has a major role. QoE requirements can be very different with respect

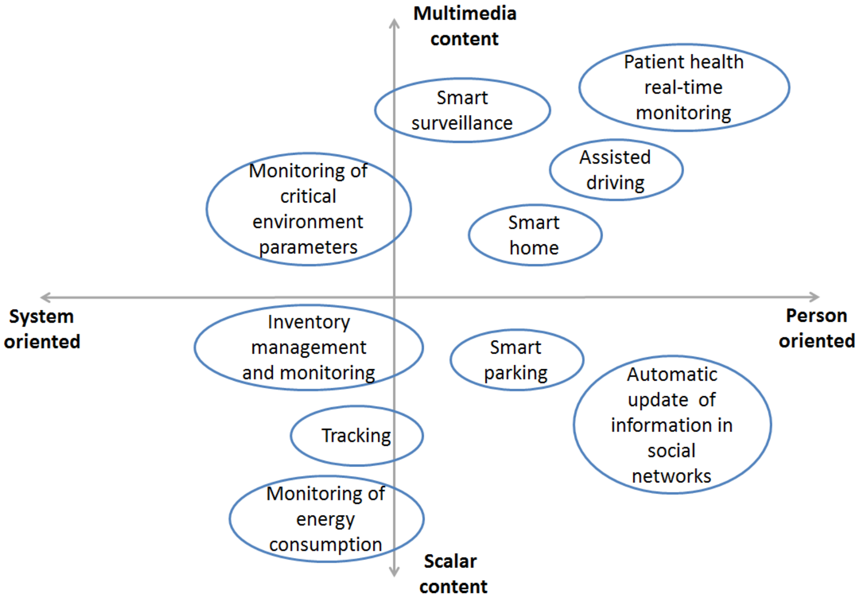

Figure 3.16: Classification of IoT applications on the basis of the type of information they manage (multimedia or scalar content) and of the type of recipient (person or system oriented).

to the considered IoT application domain; furthermore, QoE requirements can also be different among IoT applications belonging to the same IoT domain. This is also shown in Figure 3.16, where the distribution of IoT applications that are representative for each IoT domain is presented. These are placed on the picture on the basis of the type of information they manage (multimedia or scalar content) and the type of end-user orientation (person or system oriented). A person-oriented IoT application means that people have a fundamental role in the evaluation of the IoT application, since they are the end-users who benefit from the information and content provided by the IoT application. On the other hand, a system-oriented IoT application refers to those applications that automatically acquire, control and manage data in order to do specific tasks and make specific decisions. In these applications, human intervention and evaluation are not essential. Nonetheless, human participation must always be considered also for system-oriented applications, for which humans have the task of *smart* controllers and users.

However, the emerging categories of IoT objects tend to be mobile, multi-sensorial and smart, such as wearable sensors, smartphones and smart vehicles, which more and more introduce multimedia content into the service chain. By adding the multimedia content to the IoT definition, the Multimedia IoT (MIoT) can be defined as a *"network of interconnected objects capable to acquire multimedia contents from the real world and/or present information in a multimedia way"*. In the same way, multimedia objects can be defined as *"objects capable to acquire multimedia contents from the physical world, being equipped with multimedia devices such as cameras and microphones"*. This definition includes the IoMT & W concept mentioned in [78], as the latter focuses on the devices that are capable of performing at least one audio/visual sensing or actuating action. However, the MIoT refers to all of the layers in the IoT, where the multimedia flows are processed, analyzed, merged and stored in each layer for their respective purposes. It also includes the presentation layer where multimedia content can be used to present the relevant application results and control functions.

In the MIoT, three different scenarios can be distinguished on the basis of the use of the multimedia content:

1. Multimedia as IoT input and output: the multimedia content is acquired by multimedia objects, and it is presented in a multimedia way by an IoT application;
2. Multimedia as IoT input: the multimedia content is acquired by multimedia objects, and it is used by an IoT application to provide a determined service;
3. Multimedia as IoT output: IoT objects acquire signals, data and information (scalar content) that are presented in a multimedia way (e.g., by using graphs, animations, etc.) by an IoT application.

The first scenario is represented by the use case depicted in Figure 3.17(a), where some surveillance cameras record images and audio of a place. This multimedia information is collected by an IoT application and presented in a multimedia way (images, videos, audios) in order to provide a remote security control service. Figure 3.17(b) illustrates the second scenario. A camera records some images of people who want to enter in a place where the entrance is allowed only to authorized persons. The images recorded by the camera are then sent to an IoT platform where an application is deployed that consists of an identification software that has to determine if the person recorded by the camera is authorized to enter to that place. Once the software identifies the person, a command is sent to the door actuator to open the door. Otherwise, the door stays closed, and access is denied. Finally, Figure 3.17(c) shows the last case. Various IoT objects measure some medical parameters of a patient (e.g., temperature, pulse, pressure), which are then collected by the IoT platform. This application has the task to present the status of the patient in a multimedia way, for example by using graphs, animation, alarms, etc.

3.5.3 QoE layered model for MIoT applications

As already discussed, there is not a reference model for evaluating the QoE of IoT (and then MIoT) applications, probably due to the lack of a reference IoT architecture and to the different requirements of IoT applications belonging to different domains of utilization. The proposed

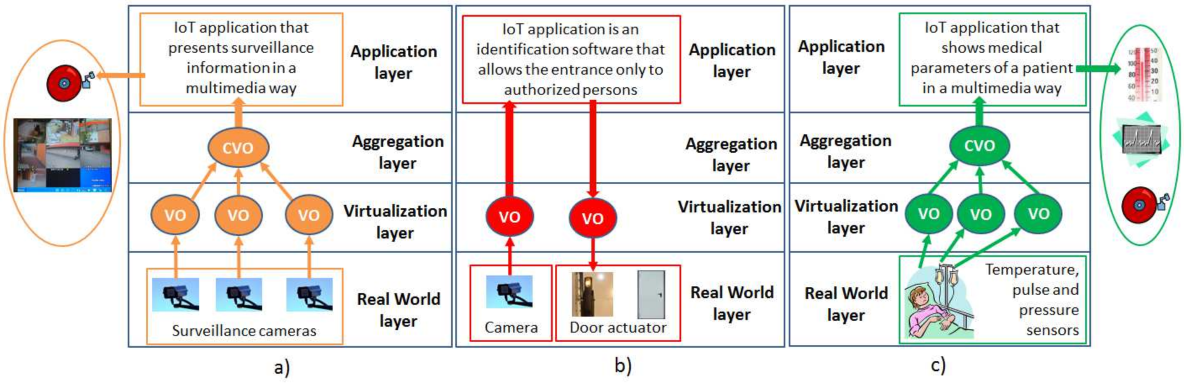

Figure 3.17: Multimedia IoT (MIoT) scenarios: (**a**) multimedia as IoT input and output: IoT application that presents in a multimedia way information acquired by multimedia objects; (**b**) multimedia as IoT input: IoT application that uses information acquired by multimedia objects; (**c**) multimedia as IoT output: IoT application that presents in a multimedia way information acquired by IoT objects (scalar content).

contribution in this direction is to leverage a layered-based approach for evaluating and controlling the QoE of MIoT applications, in which people are involved as the end-users of the multimedia content. Similarly to the model presented in Section 3.1, the choice of the layered approach is due to the objective to evaluate different categories of QoE influence factors in different layers and then to combine these measures in order to maximize the final QoE perceived by the user using the IoT application. Indeed, the layered approach has been widely used in past works in both the multimedia and IoT scenarios (as discussed in Section 2.1.2) as it allows for defining each layer singularly and independently from the others. Each layer focuses on a specific QoE domain (set of factors), so that the overall quality can be computed as a combination of all domains. The proposed model is meant to be as general as possible, so to be valid for, or at least adaptable to, any scenario for MIoT.

On the basis of the four-layer IoT architecture presented in Figure 3.15, the proposed layered QoE management framework includes a set of modules that can be integrated in the IoT architecture and are capable of evaluating and controlling the QoE of the multimedia IoT applications. The proposed layered QoE management framework is shown in Figure 3.18 and is composed of five layers: the Physical devices layer, the Network layer, the Virtualization layer, the Combination layer and the Application layer. The influence of the Context layer on the QoE is considered within the Application layer.

Physical devices layer

In this layer, the physical devices (PDs) are considered, i.e., the RWOs, which are classified in multimedia objects and scalar objects: the former are the objects capable of acquiring multimedia content, whereas the latter are the objects capable of acquiring scalar content. The informa-

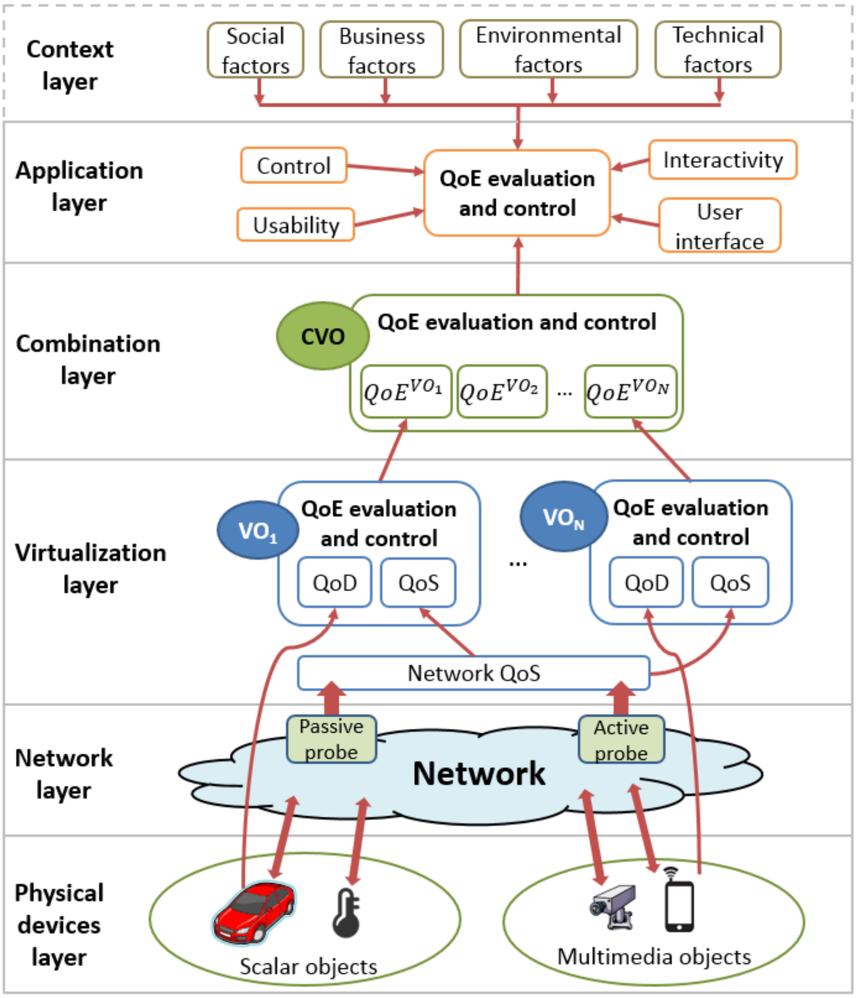

Figure 3.18: The proposed layered QoE management framework.

tion acquired by both of these two types of objects is sent to their associated VOs through the network on the basis of the network interface of the RWO. This layer focuses on the quality of the data (QoD) acquired by the PDs and taken into account at the virtualization layer. For example, the performance of a GPS receiver can be determined by measuring the accuracy and precision of the acquired position, which is the QoD. Furthermore, the QoD of a video sequence recorded by a camera accounts for the image resolution, the frames per second and the video coding distortion. Indeed, as the VO is the digital counterpart of the PD, in our view, it also takes care of managing the QoD according to the registered PD characteristics.

Network layer

The network layer accounts for the network infrastructure on which the IoT platform is based. In this layer, typical QoS parameters capable of measuring the performance of data transmission are considered, such as delay, bandwidth, packet loss, jitter, etc. The network's performance can be measured using passive or active probes. Passive probes are non-intrusive network monitoring agents that collect data without causing additional traffic overhead on the network, whereas active probes send dedicated measurement packets to benchmark the network performance. The measurements collected by the probes are sent to the network QoS module of the Virtualization layer, whose role is the execution of statistical analysis on the data collected for evaluating the quality of the network.

Virtualization layer

In the virtualization layer, the VOs are created, which are processes typically instantiated in the cloud. Each VO is provided with a VO template that can be associated with one or more PDs of which it virtualizes the functionalities. In the IoT cloud platform, the users have to choose a VO template to be associated with their PDs, if existing, or they can create a proper VO template. In fact, each VO template should be defined by the brand of the PD and is basically composed of a description of the device and a list of the device's parameters corresponding to the scalar and/or multimedia contents that can be acquired by the PD. Otherwise, the owner of the object can define a proper VO template for his/her device. The network QoS module has the task to receive the measures collected by the network probes and to create statistical analysis about the network traffic for evaluating the QoS provided by the network. Each VO can use this network information by considering the network parameters of interest for estimating the QoS of the network. As a consequence of network impairments, the data collected by the PD may be impaired. For example, network delay may create latency problems for real-time applications, whereas packet losses may cause gaps in the data. Therefore, QoS is considered as an influence factor for the QoD acquired by a PD:

$$QoD^{PD} = f_1(QoS). \tag{3.9}$$

As shown in Figure 3.18, each VO is provided with a QoE evaluation and control module, which has to evaluate and control the overall QoE provided by the VO. The QoE is evaluated by considering the influence of both QoD and QoS parameters on the QoE perceived by the users:

$$QoE^{VO} = f_2(QoD^{PD}) = f_2(f_1(QoS)). \tag{3.10}$$

This can be done by considering quality models able to map objective measures (QoS and QoD) with the subjective perceptions of the users in terms of the Mean Opinion Score (MOS). If specific models do not exist, objective metrics can be used or subjective assessments should be conducted to define the needed QoE mapping models. QoS parameters are estimated on the basis of the information provided by the network QoS module by considering only the network parameters of interest for the VO. On the other hand, the QoD refers to the quality of the content acquired by the PD. For example, the QoE of a video acquired by a camera could be a function of the video bitrate, resolution, codec and quantization parameters used for acquiring and encoding the video; the QoE of a temperature sensor could be a function of the precision and accuracy of the temperature sensor. The device parameters to be considered for evaluating the QoE of each PD are listed on its VO template. The QoE evaluation and control module is also capable of controlling the QoE of the VO, which means that it can order the PD associated with the VO to modify the value of its parameters if possible; for example, for the case of a camera, it can order to reduce or increase the resolution or bitrate used for acquiring the video. The modification of these parameters brings a modification of the QoE perceived by the users.

Combination layer

In the combination layer, the CVOs are created. As said before, the CVO is composed of various VOs with the aim of combining their functionalities to provide a determined service, which a single VO cannot accomplish. Furthermore, the CVO has to evaluate the overall QoE provided by the VOs, which are composing it. Therefore, the CVO is provided with a QoE evaluation and control module that has to properly combine the influence of each VO on the QoE perceived by the users:

$$\begin{aligned} QoE^{CVO} &= f_3(QoE^{VO_1}, QoE^{VO_2}, \ldots, QoE^{VO_N}) = \\ &= f_3(f_2(QoD^{PD_1}), f_2(QoD^{PD_2}), \ldots, f_2(QoD^{PD_3})), \end{aligned} \tag{3.11}$$

where for each PD, the QoD is a function of the QoS, as in Eq. (3.9). For example, the QoE can be estimated with a mathematical model that combines and weighs each single quality contribution provided by the VOs in order to achieve the maximum quality for the requested service. The QoE evaluation and control module is also capable of controlling the QoE of the CVO, which means that, on the basis of the single contribute provided by each VO, it can order the VOs to modify the value of their parameters, if possible, to maximize the QoE. This order is then propagated from the VOs to their PDs.

Application layer:

The application layer considers the QoE provided by MIoT applications in terms of control, interactivity, presentation and usability. In fact, independently from the quality of the multimedia content provided by the application, the quality perceived by the end-users is also influenced by the presentation of the contents to the user, the application interface, the degree of interactivity and the controllability and usability of the application. The QoE evaluation and control module evaluates the influence of these parameters on the QoE. Furthermore, it also considers the influence of the context factors on the application. The context of use concerns many different factors, such as: the type of device on which the application is used (technical factors); the people with which the end-user consumes the application (social factors); the application costs (business factors); and the place where the application is used (environmental factors). Context parameters can be determined by the application through information provided by the users by means of their user profiles, surveys and/or hardware/software able to automatically determine information related to the device in which the application is running, the place where the user is located (for example with a GPS sensor) and other factors.

Therefore, the final QoE perceived by the users can be expressed as:

$$QoE^{App} = f_4(QoE^{CVO}, AppFactors, ContextFactors). \quad (3.12)$$

where *AppFactors* and *ContextFactors* are the influence factors concerning the application and the context of use, respectively. To evaluate how these influence factors impact the QoE of the users, subjective assessments have to be conducted.

3.5.4 Analysis of use case: MIoT vehicle application

In order to provide an example of the application of the proposed QoE management framework and its layered approach on real MIoT applications, an MIoT vehicle application has been implemented. The objective is to show how quality models can be defined for the VOs as a function of QoS and QoD parameters and how these QoE models can be combined by the CVO for evaluating the overall QoE of an MIoT application. Finally, a subjective quality assessment has been conducted for validating the resulting QoE models.

MIoT vehicle application

An IoT multimedia system aimed at remote monitoring and tutoring practitioners when driving a car has been developed. The objective of this application is to show in a multimedia way and in real time the state and the position of the vehicles during driving lessons together with a video showing a view of the roads traveled by these vehicles. In this way, the instructors can remotely monitor and evaluate the results achieved by the practitioners.

Figure 3.19 shows the proposed QoE framework applied to this specific vehicle application. The physical devices layer accounts for the physical devices acquiring the information needed by the application; these are an Arduino Mega 2560 [124], the Telit UE910-EUR and SL869 modules [125], and a camera. The Arduino Mega 2560 is connected to the On-Board Diagnostic interface (OBD-II) of the vehicle and is able to acquire vehicle parameters. For this use case, the speed and revolutions per minute (rpm) parameters were acquired. The Telit SL869 module is provided with a Global Positioning System (GPS), which acquires the position coordinates of the vehicle with the current date and time. The vehicle data collected by the Arduino

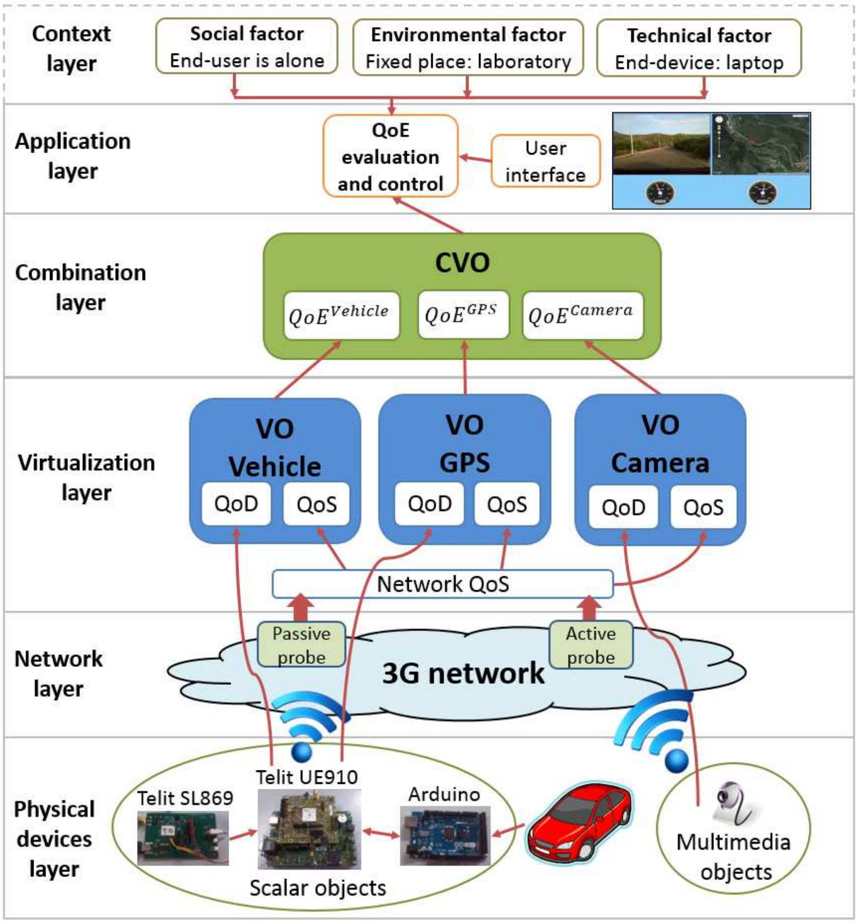

Figure 3.19: Framework of the MIoT vehicle application for remote tutoring for driving school lessons.

and the SL869 are sent to the IoT platform (which is in the cloud) by the UE910-EUR, which is provided with 3G connection and acts as a network interface between the sensors and the IoT platform. Simultaneously, the camera installed in the vehicle cabin records and sends to the IoT platform the video sequences of the road traveled by the vehicle through the 3G network.

In the network layer, the performance of the 3G network used by the physical devices for communicating with the VOs is taken into account. In the virtualization layer, three VOs are created: the VO of the vehicle receives the vehicle speed and rpm data; the VO of the GPS receives the coordinates of the vehicle position; the VO of the camera receives the videos recorded by the camera. In the combination layer, a CVO is created that receives the data acquired by the three VOs; herein, the vehicle parameters, the GPS coordinates and the video sequences (the images recorded by the camera are tagged with the date and time) are analyzed and synchronized. Finally, in the application layer, the combined information provided by the CVO is shown in a multimedia way to the users on a web application. Specifically, the web MIoT application shows in a web page a video of the road traveled by the vehicle, a map in which is shown the vehicle position (highlighted with a moving red circle) and the speed and rpm of the vehicle.

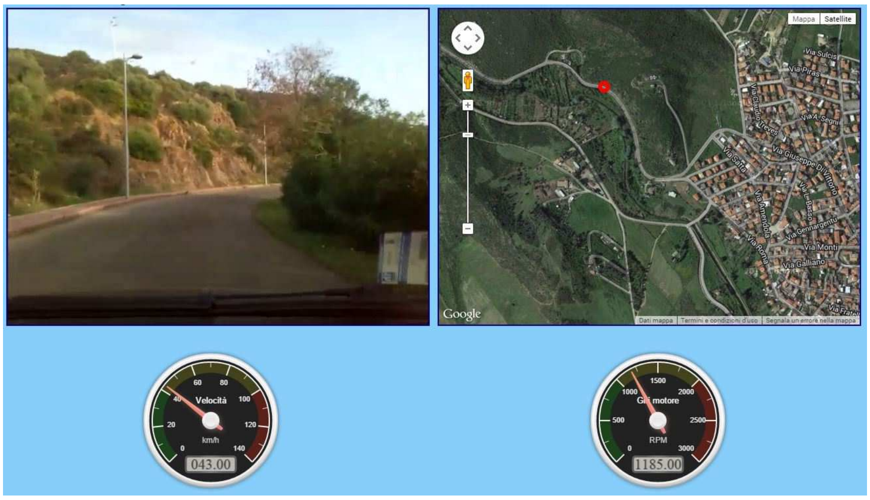

Figure 3.20: Screenshot of the web MIoT application with analog speed and rpm indicators.

Figure 3.21: Screenshot of the web MIoT application with digital speed and rpm indicators.

Figures 3.20 and 3.21 show a screenshot of the web MIoT application where speed and rpm parameters are shown to the users with analog and digital indicators, respectively.

Subjective evaluation procedure

Test Conditions (TCs) for conducting a subjective quality assessment and determining the QoE of the vehicle MIoT application have been defined and are summarized in Table 3.9

The parameters chosen to create the TCs are:

- Video bitrate: it is the QoD parameter for the video content recorded by the camera. Six different videos were recorded and encoded at two different bitrates: 700 kbps for low video quality and 1.5 Mbps for high video quality. The videos were encoded with the MPEG-4 codec at a resolution of 640×480 pixels and a frame rate of 24 fps.
- Accuracy of vehicle data: it is the amount of data correctly acquired by the physical devices. In this case, it is the QoD parameter for the Arduino and

Table 3.9: Test Conditions (TC).

TC	Video	Video Bitrate	Accuracy of Vehicle Data	Network Delay	Data Presentation
1	Video 1	1.5 Mbps	100%	0 s	Analog
2	Video 2	1.5 Mbps	100%	0 s	Digital
3	Video 3	1.5 Mbps	100%	3 s	Analog
4	Video 4	1.5 Mbps	100%	3 s	Digital
5	Video 5	1.5 Mbps	75%	0 s	Analog
6	Video 6	1.5 Mbps	75%	0 s	Digital
7	Video 1	700 kbps	100%	0 s	Analog
8	Video 2	700 kbps	100%	0 s	Digital
9	Video 3	700 kbps	100%	3 s	Analog
10	Video 4	700 kbps	100%	3 s	Digital
11	Video 5	700 kbps	75%	0 s	Analog
12	Video 6	700 kbps	75%	0 s	Digital

GPS devices. Artificially errors were introduced in the data acquisition by modifying the value for 25% of the data acquired by these two devices. With regard to speed and rpm, modified values were replaced with random values in the range $\pm 100\%$ with respect to the acquired value, whereas for the vehicle position, the acquired coordinates were modified to shift the vehicle position for a maximum of 10 m with respect to the acquired position (again, the position was generated randomly in the distance range of 0–10 m). Modified parameters were shown randomly to the user (on average, one out of four values were modified) and could also happen sequentially.

- Network delay: it is the QoS parameter of the 3G network used by the UE910 module (the network delay for the network used by the camera was not consider to obtain a desynchronization between the video sequences and the vehicle data). In some TCs, a network delay of 3 s involves the web application showing delayed values of GPS, speed and rpm data with respect to the video sequences. Network delays are introduced in a way that the user can notice them, for instance when the vehicle is starting or stopping.
- Data presentation: it is an application influence factor. Vehicle data (speed and rpm) are presented to the users with both analog and digital indicators, as in Figures 3.20 and 3.21.

For QoE evaluation, a subjective quality assessment has been conducted involving 24 people, which were asked to rate the quality of the MIoT application with regard to the 12 TCs summarized in Table 3.9. The assessment started with a pre-test phase, during which the user was provided with short written instructions and with a brief detailed oral explanation. Furthermore, some TCs were shown in order to give each user an overview of the video qualities and data corruptions involved in the experiment. The parameters that the user had to consider in the subjective evaluations were: the video quality; the synchronization and accuracy of the vehicle data with respect to the video; the overall presentation of the vehicle data.

For subjective tests, the single-stimulus Absolute Category Rating (ACR) method has been adopted [34], which consists of presenting the TCs one at a time and allowing for their independent evaluation on a category scale. The following five-level ITU scale for rating overall quality has been used: 5 stars (Excellent), 4 stars (Good), 3 stars (Fair), 2 stars (Poor), 1 star (Bad). The scores assigned by the observers have been averaged in order to obtain the Mean Opinion Score (MOS). The device employed for the subjective quality assessment was a laptop with an LCD display with a resolution of 1440×900 pixels and an aspect ratio of 16:9. The web MIoT application was displayed on the Google Chrome browser in full-screen mode while each subject was wearing earphones. Each TC lasted for 40 s, and the assessment has been carried out in a 15 min-long session. A rating page was automatically displayed after the end of each TC, where each subject had to select a discrete value between one and five indicating the overall quality of the TC just shown. The voting phase was not time limited, and after each vote, the subjects were asked to confirm their choice. Upon confirmation, a 10-s pause was imposed, then the next TC would be automatically activated. Such an automatic procedure was iterated for all 12 TCs. The presentation order of the TCs has been randomized for each subject.

Results of the assessment

The MOS was computed from subjective results for each TC, together with the 95% confidence interval. Figure 3.22 shows MOS results comparing low and high video qualities being equal in the other conditions, whereas Figure 3.23 shows MOS results comparing the analog and digital presentation of vehicle parameters being equal in the other conditions.

From Figure 3.22, MOS results show that video quality does not influence very much the QoE of the vehicle MIoT application. In fact, being equal in the other conditions, the MOS for low and high video quality have more or less the same value. This means that, in this specific application, the end-users are more interested in the accuracy and synchronization of the vehicle data than in the quality of the video sequences. With regard to the presentation of the vehicle data, MOS for digital data presentation have, in the majority of cases, slightly higher values than MOS for analog data presentation, as shown in Figure 3.23. In fact, except for TCs concerning delayed data (TC_3, TC_4, TC_9, TC_{10}), the users preferred digital data visualization. This could

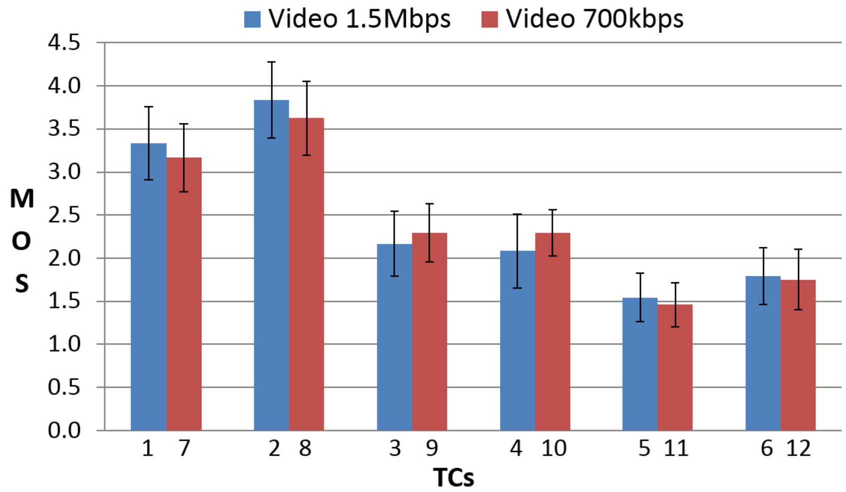

Figure 3.22: MOS results with the 95% confidence interval comparing low and high video qualities being equal in the other conditions.

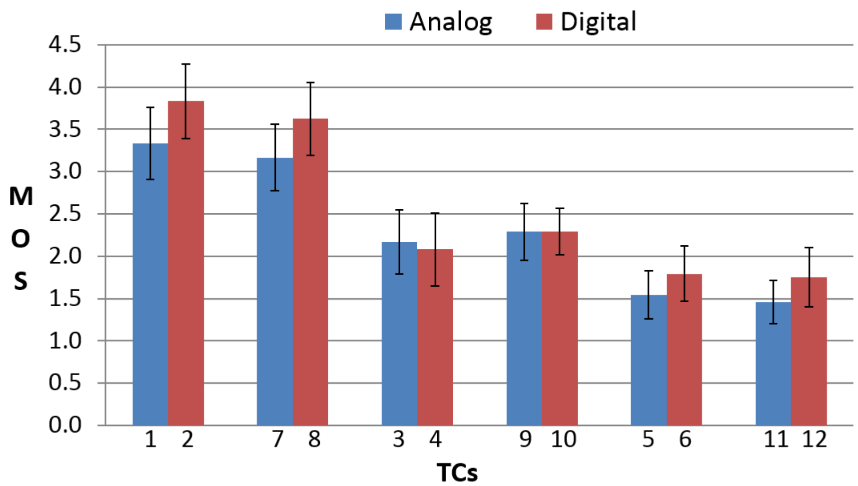

Figure 3.23: MOS results with the 95% confidence interval comparing analog and digital presentation of vehicle parameters being equal in the other conditions.

be due to the fact that digital indicators are more precise than analog indicators since the user can know the exact values of the vehicle speed and rpm.

Furthermore, MOS results show that the most annoying TCs are those where wrong vehicle data are displayed (TC_5, TC_6, TC_{11}, TC_{12}). Then, the accuracy of the data is the most relevant parameter considered by the end-users. TCs with delayed data also annoy the end-users, but to a lesser extent (TC_3, TC_4, TC_9, TC_10). The evident result is that from this vehicle MIoT application, the end-users expect the displaying of accurate and synchronized vehicle data; otherwise, they were annoyed. On the other hand, video quality and data presentation do not have a great influence on the QoE.

Quality models

As discussed previously, each VO is provided with a QoE evaluation module that has the role of evaluating the QoE of the data received by its associated physical device as a function of the QoD and QoS parameters. Specifically, in this case, the VO of the camera evaluates the QoE as a function of the video bitrate (Rate), whereas the VOs of the vehicle and the GPS evaluate the QoE in function of the accuracy (Acc) of vehicle data and the delay (Delay) of the 3G network.

The subjective ratings provided by the users have been divided into two datasets: a training dataset composed of the ratings provided by the first 12 subjects and a validation dataset composed of the ratings provided by the last 12 subjects. MOS_T and MOS_V values were computed respectively from the training and validation datasets. For modeling and mapping the QoE as a function of the QoD and QoS parameters, a linear (l) and a logarithmic (nonlinear (nl)) regression functions were considered between inputs (QoS and QoD) and output data (QoE, i.e., MOS_T).

$$QoE_l^{Camera} = a_{1l} \times Rate + K_{1l} \tag{3.13}$$

$$QoE_l^{Vehicle} = a_{2l} \times Acc + K_{2l} + a_{3l} \times Delay + K_{3l} \tag{3.14}$$

$$QoE_l^{GPS} = a_{2l} \times Acc + K_{2l} + a_{3l} \times Delay + K_{3l} \tag{3.15}$$

$$QoE_{nl}^{Camera} = K_{1nl} \times (a_{1nl})^{Rate} \tag{3.16}$$

$$QoE_{nl}^{Vehicle} = K_{2nl} \times (a_{2nl})^{Acc} \times K_{3nl} \times (a_{3nl})^{Delay} \tag{3.17}$$

$$QoE_{nl}^{GPS} = K_{2nl} \times (a_{2nl})^{Acc} \times K_{3nl} \times (a_{3nl})^{Delay} \tag{3.18}$$

Eqs. (3.13)–(3.18) are the models that describe the relation between the QoS and QoD parameters and the QoE of the VOs. Two regressions have been computed: one for the TCs considering digital data presentation and one for the TCs considering analog data presentation. The coefficients obtained by computing these regressions are summarized respectively in Tables 3.10 and 3.11 and are valid for Eqs. (3.13)–(3.18).

Table 3.10: Values of the coefficients for the linear regression in Eqs. (3.13)–(3.15).

Coefficient	a_{1l}	K_{1l}	a_{2l}	K_{2l}	a_{3l}	K_{3l}
Value (digital)	0.0000	2.5556	0.0483	−1.8750	−0.2153	2.7708
Value (analog)	0.0000	2.3056	0.0558	−2.8125	−0.0903	2.3958

Table 3.11: Values of the coefficients for the nonlinear regression in Eqs. (3.16)–(3.18).

Coefficient	a_{1nl}	K_{1nl}	a_{2nl}	K_{2nl}	a_{3nl}	K_{3nl}
Value (digital)	1.0000	2.5085	1.0194	0.4140	0.9366	2.5740
Value (analog)	1.0000	2.1597	1.0273	0.1829	0.9930	2.1666

In the previous section, from the analysis of MOS, it resulted that video quality does not influence the QoE, and the data regressions confirm this result; in fact, the linear and nonlinear coefficient values (a_{1l} and a_{1nl}) for the rate parameter in Eqs. (3.13) and (3.16) are zero and one, respectively, i.e., the identity elements of the addition and multiplication operations. Therefore, the value of the Rate does not influence the QoE. However, this could also be due to the limited and closer values of bitrates chosen for coding the video.

In the combination layer, the QoE model of the CVO combines the QoE provided by each VO to evaluate the overall QoE. Therefore, the composite linear and nonlinear QoE models of the CVO are as follows:

$$QoE_l^{CVO} = a_{1l} \times Rate + K_{1l} + a_{2l} \times Acc + K_{2l} + a_{3l} \times Delay + K_{3l} \tag{3.19}$$

$$QoE_{nl}^{CVO} = K_{1nl} \times (a_{1nl})^{Rate} \times K_{2nl} \times (a_{2nl})^{Acc} \times K_{3nl} \times (a_{3nl})^{Delay} \tag{3.20}$$

Since it resulted that the Rate parameter does not influence the QoE, these equations become:

$$QoE_l^{CVO} = a_{2l} \times Acc + K_{2l} + a_{3l} \times Delay + K_{3l} \tag{3.21}$$

$$QoE_{nl}^{CVO} = K_{2nl} \times (a_{2nl})^{Acc} \times K_{3nl} \times (a_{3nl})^{Delay} \tag{3.22}$$

Finally, at the application layer, the QoE evaluation and control module must decide which coefficients to use from Tables 3.10 and 3.11 for Eqs. (3.19)–(3.22). This decision must be made according to the user interface of the application that can present vehicle data with digital or analog indicators. Tables 3.12 and 3.13 summarize the Pearson correlation values computed between the MOS_V values and the quality models defined in Eqs. (3.19)–(3.22) respectively with

Table 3.12: Values of the Pearson correlation between the MOS_V values and the quality models defined in Eqs. (3.19)–(3.22) with regard to the digital data presentation.

Quality Model	**Eq.** (3.19)	**Eq.** (3.20)	**Eq.** (3.21)	**Eq.** (3.22)
Pearson correlation	0.97	0.94	0.97	0.95

Table 3.13: Values of the Pearson correlation between the MOS_V values and the quality models defined in Eqs. (3.19)–(3.22) with regard to the analog data presentation.

Quality Model	**Eq.** (3.19)	**Eq.** (3.20)	**Eq.** (3.21)	**Eq.** (3.22)
Pearson correlation	0.93	0.87	0.93	0.87

regard to the digital and analog data presentation. The Pearson correlation results are very high, especially for the linear model, which means that the proposed linear model is highly correlated with subjective evaluation and can be used to estimate and control the QoE of the vehicle MIoT applications. Furthermore, these results confirm the validity of the proposed layered QoE model, which allows combining the single QoE contributions in order to evaluate the overall QoE perceived by the users. Pearson correlation values were computed for both the equations considering/not considering the Rate parameter for further demonstrating that the inclusion of this parameter in the model does not bring a better precision in quality prediction.

In a future implementation, the QoE evaluation and control module of the combination layer should automatically notice that the Rate parameter has no influence on the QoE: a higher video bitrate requires high bandwidth without increasing the QoE of the end-users. Therefore, the CVO controller can order the VO of the camera to acquire the video at a low bitrate to save bandwidth. In a more complex scenario, the control module could make further decisions. For instance, if the proposed MIoT vehicle application would allow the end-user application to interact with the vehicle (e.g., to reduce the speed), the controller will have to find a trade-off between synchronization of the different data flows and data presentation delay. Precisely, if the video sequence and the data vehicle are not synchronized, due to network delay, the controller can hide this delay by buffering and synchronizing the data before the displaying on the web IoT application, in order to increase the end-user QoE. However, in this case, the end-user interaction with the application will not be in real time. For this reason, the controller has to find a trade-off between data desynchronization and real-time interaction.

3.6 Conclusions

QoE modelling aims to define the relationship between different measurable QoE influence factors (IFs) and quantifiable QoE dimensions for a given service scenario. Due to the huge number of possible IFs that can affect the QoE, it is very difficult to define a QoE model able to provide a mathematical relationship considering the impact of all the relevant IFs on the QoE perceived for a specific service. Additionally, the definitions of the models and their factors often follow different approaches, making it difficult to compare the proposed methods and to combine their results in the effort of achieving better performance. This has brought to the problem of modelling un-interoperability, which is herein defined as the unfeasibility (or at least difficulty) of integrating the results of different modelling activities to broaden the range of scenarios where the integrated model can be applied. To address the un-interoperability issue, a layered modelling approach for evaluating the QoE of multimedia services is proposed. Accordingly, the models are defined in terms of separate layers, each devoted to a specific QoE domain (set of factors), so that the overall quality can be computed as a combination of all domains. To demonstrate the validity of the proposed layered model, the influence of system and interactivity IFs on the QoE perceived by the users when streaming video sequences on tablet devices are evaluated and combined for the estimation of the overall QoE. The results showed that the interactivity provides an increase of the perceived quality respect to the video without interactivity. Therefore, the influence of the interactivity on the video quality can be considered separately from the influence of system IFs, and it has been successfully translated into both an additive or multiplicative parameter in existing quality models. This means that IFs belonging to different layers can be firstly considered independently and then be combined for estimating the overall QoE. These preliminary results validate the proposed layered model although additional investigation is needed to confirm the obtained results.

Additionally, the influence of device switching on the QoE perceived by users watching video contents was investigated. The aim was to demonstrate that the QoE is not only related to the video consumption on the single device, but it takes into consideration the overall experience of watching the whole video by switching between different devices; for this reason, two devices with very different characteristics and technical capabilities were deliberately chosen, i.e., a TV screen and a tablet. Finally, the following conclusions are reached: low video qualities achieve higher MOS values when the viewing device is a tablet rather than a TV screen; similarly, many users perceived a slight increase in the quality when switching from the TV screen to the tablet, even in the case the quality is kept constant, without a strong effect on the MOS ratings, however. QoE for video quality switching is in line with the average MOS for the constant quality scenario at the considered quality levels. Nevertheless, in this case a QoE model has not been defined because this scenario is too specific. Indeed, the reverse scenario of device switching from a tablet to the TV, and the consideration of additional devices, such as smartphones, are subjects of future works.

Finally, a first approach to QoE modelling for Internet of Things is discussed. First, the concept of Multimedia IoT (MIoT) is introduced in order to focus on the applications in which people are involved as the end-users of the multimedia content provided by the MIoT applications. Then, a layered QoE management framework is proposed, which aims at evaluating and controlling the contributions of each IF to estimate the overall QoE in MIoT applications. Finally, as a practical use case, a vehicular MIoT application is implemented, which shows in a multimedia way and in real time the state and the position of vehicles during driving lessons together with a video showing a view of the roads traveled by these vehicles. A subjective quality assessment has been conducted to verify the applicability of the proposed approach, where the parameters that the user had to consider in the subjective evaluations were: the video quality; the synchronization and accuracy of the vehicle data with respect to the video; the overall presentation of the vehicle data. Results showed that end-users are more interested in the accuracy and synchronization of the vehicle data than in the quality of the video sequences. Furthermore, the QoE predicted by the proposed QoE model is highly correlated with subjective results, which means that it can be used to estimate and control the QoE of the vehicle MIoT application. However, further investigations are needed and additional experiments should be performed with other MIoT applications to verify the model and to introduce further refinements.

Chapter 4

QoE application scenarios

This chapter focuses on two different application scenarios in which the Quality of Experience (QoE) is involved as a metric for system optimization and user profiling. The first application scenario investigates the role of the QoE in the collaboration between Internet Service Providers (ISP) and Over The Top (OTT) services and is discussed in Section 4.1. The provision of QoE is considered as the common objective for OTTs and ISPs because delivering good QoE helps to decrease the user churn, i.e., the user leaving a service, and consequently to increase the revenue. However, individually, the ISP and the OTT have limited resources for QoE provision: the ISP has the control of the network but it is not able to measure the QoE perceived by the users; on the other hand, the OTT is aware of the QoE perceived by the users but does not have any control on the network. Therefore, a QoE-aware collaboration approach between ISP and OTT has been proposed, which is driven by the maximization of the revenue based on different factors, such as the user churn, pricing and marketing actions. The collaboration is guided by the ISP, which maximizes the revenue as a function of the delivered QoE with the provision of better network resources on the basis of the context-aware QoE monitoring provided by the OTT. Simulations are conducted to analyze the potential of the proposed collaboration approach with respect to an approach that does not consider a collaboration between the OTTs and the ISP so that the OTTs deliver their contents through the best effort service over the ISP network.

In the second application scenario, presented in Section 4.2, the QoE is measured for user profiling and a posteriori evaluation of the customer comfort in a Smart Home Energy Management (SHEM) system. In the proposed system, the QoE is considered as the degree of annoyance perceived when the starting time or the set temperature of appliances in a Smart Home is modified with respect to users' preferences. A survey has been conducted to collect users' preferences, which have been clustered in different profiles. Based on these results and on the created profiles for each appliance, a Smart Home environment has been created where smart appliances can be easily installed and the proper profile for each user is assigned. The SHEM runs a task scheduling model, which relies on two algorithms: the QoE-aware Cost Saving Appliance Scheduling (Q-CSAS) algorithm that is aimed at scheduling controlled loads based on users profile preferences and Time-of-Use (TOU) electricity prices; and the QoE-aware Renewable Source Power Allocation (Q-RSPA) algorithm that modifies the working schedule of appliances whenever a surplus of energy has been made available by renewable sources. The final objective is that of scheduling the appliances operations, such as starting time and set temperature, so that a trade-off between energy expenses and annoyance perceived is achieved. The performance of the proposed QoE-aware SHEM system are compared with respect to the case of a QoE-unaware system (which only optimizes the starting time with reference to cost saving), in terms of energy cost savings and annoyance rate.

Finally, Section 4.3 concludes the Chapter.

4.1 QoE-aware collaboration among OTTs and ISPs

The provision of QoE is considered as the common objective for both OTTs and ISPs. Indeed, it is a matter of fact that the proper management of QoE brings to direct economic advantages; in fact, if a customer does not receive adequate QoE, it is more likely to become a churner, i.e, a customer leaving the service. However, individually, the ISP and the OTT have limited resources for QoE provision: on the one hand, the ISP has the control of the network but it is not able to measure the QoE perceived by the users; on the other hand, the OTT is aware of the QoE perceived by the users but does not have any control on the network. Accordingly, as the OTTs applications are being delivered over the ISPs best-effort Internet without considering the resource requirement of the application, the degradation may lead to serious user churn. Furthermore, as the network resource requirements vary in accordance with QoE model of the application, only an OTT may know the best application-aware QoE model according to the users' context of use. Moreover, today the OTT services are being encrypted with the concern of the user privacy issues. The traffic encryption is leading to a major challenge for application-aware service delivery as ISPs may not be able to either perform the Deep Packet Inspection (DPI) and packet marking to apply traffic engineering concepts such as packet prioritization, traffic shaping, admission control, etc. In addition, the recent drastic increase in the use of multimedia services requires more resources at the ISPs end to assure the required level of quality to the users, although ISPs are not in the loop of revenue generation between the OTTs, which provide the multimedia services, and the users. Indeed, the ISPs, as well as the OTTs, are affected by the reaction of the users to low service quality, and must face the risk of user churn which may result into decrease of market share and reputation which is unavoidable in this era of strong competition in this domain.

On the basis of these considerations, a QoE-aware collaboration approach between ISP and OTT is proposed. In Section 4.1.1, on the basis of the possible roles of the OTTs (QoE monitoring and application optimization) and the ISP (QoS monitoring, revenue maximization and network-wide operations), a reference architecture is proposed, which defines the interfaces and modules required for providing a baseline for continuous exchange of information/service between OTTs and ISP. In Section 4.1.2, the proposed the QoE centered collaboration approach is presented, which is driven by the maximization of the revenue based on different factors, such as the user churn, pricing and marketing actions. The collaboration is guided by the ISP which maximizes the revenue as a function of the delivered QoE with the provision of better network resources on the basis of application QoE model, while the OTTs perform the context-aware QoE monitoring and provide the ISP with the information about the class of service per user as well as about application parameters. Finally, in Section 4.1.3, simulations are conducted to analyze the potential of the proposed collaboration approach. Specifically, an ISP and 2 OTTs are considered, and their revenue generation is investigated for two different approaches: No Collaboration (NC) and Joint Venture (JV). The former does not consider a collaboration between the OTTs and the ISP so that the OTTs deliver their contents through the best effort service over the ISP network, whereas the latter is the proposed collaboration approach. Without loss of generality, two specific OTT services were considered: video streaming and VoIP.

4.1.1 Reference architecture for collaboration

The reference scenario is composed of an ISP which provides network infrastructures and services, and different OTTs that provide over the top applications. The major aspect that links the OTTs with the ISP is the QoE delivered to the final users, which can be selected as the core component for building collaboration strategies towards service delivery. As a matter of fact, the OTT is aware of users' expectations and the level of quality they are experiencing, thanks to the control of the software at the application level and a *close* relationship with the user. Indeed, through the application software it can monitor application parameters (such as buffer occupancy and playout delay in video streaming applications) and context parameters (such as the type of device and the position of the user), and can even ask the user to fill surveys about quality satisfaction. However, it cannot have any control on the network. On the other hand, the ISP is more focused on Quality of Service (QoS) and controls network resources provided to all of its users; however, not always better QoS provided has a positive effect on QoE.

Therefore, since the OTT is the entity which is more QoE-oriented, a collaboration between the OTTs and the ISP can help the ISP to implement a QoE-aware network management for the provisioning of adequate QoE to the end-users. Figure 4.1 sketches the reference archi-

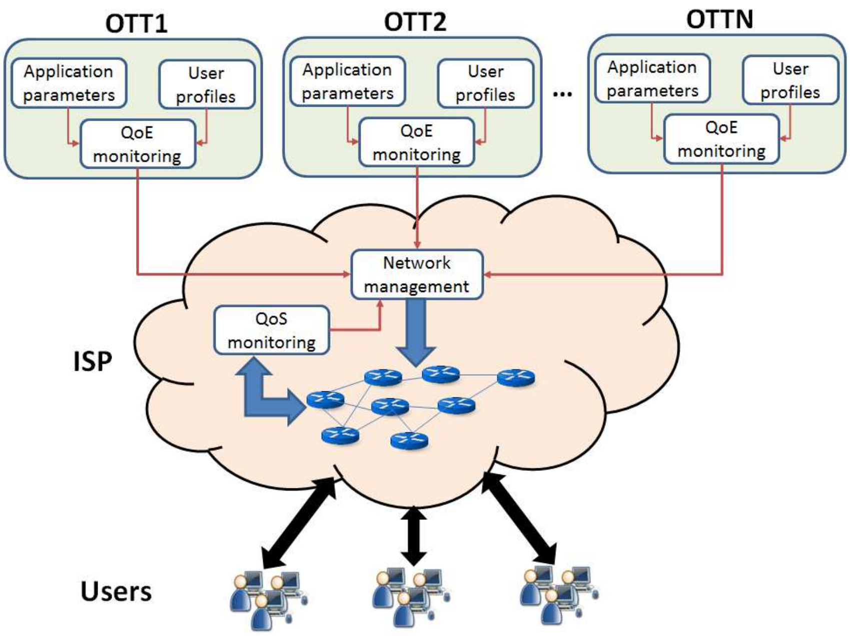

Figure 4.1: Reference architecture for the collaboration between ISP and OTTs.

tecture of the collaboration scheme. A high-level architecture is provided, which defines a set of functional requirements that must be provided by OTTs and ISP for making possible the collaboration approach. Since it is a functional architecture, any specification are provided about how to implement the functional blocks nor recommendations are given about the network interfaces to be used for information exchange. It is assumed that multiple OTTs decide to collaborate with a single ISP. The OTTs monitor the QoE of their users using QoE models which are specific for the application they are providing to their users. This is the role of the QoE monitoring block, which measures the QoE as a function of application parameters and context parameters (extracted from user profile information) such as user location, user's device, user's expectations, etc. The QoE measurements are then conveyed to the ISP trough a dedicated interface, together with the information about the class of service of the users. In fact, a dedicate communication channel is established between each OTT and the ISP, to allow for the transmission of information between OTTs and ISP. Such a channel is interconnected at both the ISP and OTT ends with a functional block implementing Authentication, Authorization and Accounting (AAA) functions for a secure information exchange.

On the other hand, the QoS monitoring block of the ISP monitors the QoS of the network through which all the OTT applications are provided to the end-users. QoS and QoE measurements are then received and collected by the Network management block, which runs a QoE-aware network management algorithm which aims at controlling the QoE by looking at its impact on the user churn and then on the revenue. Specifically, on the basis of a model of the revenue, the best combination of price and QoE level is computed using Eq. (4.5). Then, relevant requirements are taken for providing network resources to quality-demanding users for maximizing the revenue. However, these decisions must take care of not putting other users at a disadvantage neither discriminating other OTTs (for assuring Network Neutrality).

4.1.2 Collaboration model

It is assumed that the multiple OTT services are passing through an ISP network and they agree upon the collaboration on the basis of the roles and interfaces defined in the reference architecture proposed in Section 4.1.1. A single ISP is considered to simplify the treatment. However, the proposed solution can be extended to multiple ISPs scenario without any issue of scalability. Nonetheless, the proposed collaboration requires a common ground among ISP and OTTs in the form of key models related to: revenue generation, QoE, user churn, pricing and marketing.

Pricing modelling

An important point of the collaboration between the ISP and the OTTs is the definition of the pricing model, i.e., the economic rules which define how much the users should pay for accessing the combined ISP-OTT services. As analyzed in [126], network congestion brought to the birth of Smart Data Pricing (SDP), i.e., a suite of pricing and policy practices that have been proposed by operators as access pricing options instead of the traditional flat-rate model. One application of SDP is the pricing for end-user QoE, i.e., pricing strategies for matching the operator's cost of delivering bits at the consumer's QoE needs for different application types at the price the customers are willing to spend. SDP approaches are mainly classified into static and dynamic models depending on whether the prices are changed in real-time or on a longer timescale. In this case, a static model is chosen: the Paris Metro Pricing (PMP) concept for Internet pricing proposed in [127]. Although the PMP model charges different prices for different network channels, there are no guarantees of QoS for the users which pay more. However, it is expected that the channels with higher prices would be less congested than those with lower prices, resulting in higher quality provided to customers paying more.

The proposed pricing model considers an enhanced version of the PMP model, which assures a minimum guaranteed quality to the users depending on the money they pay. Accordingly, it is assumed that the services provided by the ISP-OTTs collaborations are being offered in J different levels of quality (with $j = 1, 2, 3, ..., J$ indexing the different levels) and different prices, and that the higher the price the better is the expected (and provided) quality. The users are assigned to a specific class in function of their willingness to pay W^n, where n indexes the user. For simplicity, as in [128], normalized W^n and prices are considered so that

$W^n \in [0, 1]$ and $P_{i,j} \in [0, 1]$, where $P_{i,j}$ is the price to be paid to subscribe to the j-th class of service of application i. As a general example, a user n will subscribe to the service class j if $P_{i,j} \leq W^n < P_{i,j+1}$.

Till here, this is a QoS-based pricing model which aims at providing higher system performance to users paying more, i.e., different Service Level Agreements (SLAs) are defined between the providers and the users as a function of their willingness to pay. However, SLAs are difficult to be understood by the users and are not directly related to their perceived quality. Therefore, inspired by the concept proposed in [129], the quality provided by each class of service is defined in terms of Experience Level Agreements (ELAs). An ELA is defined as *"a special type of SLA designed to establish a common understanding of the quality levels that the customer will experience through the use of the service, in terms that are clearly understandable to the customer and to which he or she can relate"*. Therefore, the quality provided by each class of service is represented with a star rating (from 1 to 5 stars), where the stars have the same meaning of the rating values defined by the Mean Opinion Score (MOS), i.e., 1 star means "Bad quality", 2 stars mean "Poor quality", 3 stars mean "Fair quality", 4 stars mean "Good quality", and finally 5 stars mean "Excellent quality". However, any other representation method can be used as an alternative.

At this point, a question arises: how can quality levels be defined? Specifically, how can the collaborating ISP-OTT providers decide which QoS and application parameters provide the users with a certain quality level? This is an important point as it is well known that the QoE depends on many different factors, ranging from objective QoS and application parameters to more subjective factors such as the context in which an application is used (used device, environment, time of the day, social factors, etc.) and human factors (user's expectation and experience, user's sensitivity, etc.). Then, it is assumed to use existing (and future) QoE models depending on the considered applications, e.g., VoIP and video streaming, which investigate how the QoE perceived by the users varies in function of network and application impairments. Some use cases are addressed in the simulation section.

Revenue modelling

Recall that the proposed collaboration is driven by the maximization of the revenue for both the service providers, for which it is needed to define an appropriate model. According with the price model proposed in the previous section, here a model for the revenue computation is provided. The OTT-ISP revenue clearly evolves over the time due to several factors, such as the price and the QoE. The revenue is then considered as a discrete-time process where t_x $(x = 0, 1, 2, ...)$ indexes the time instants at which the revenue is computed and corrections to the system are introduced. Furthermore, the time window $T = t_{x+1} - t_x$ is defined as the period of time during which the prices of the classes of service and the number of users belonging to each class are static.

The combined revenue for the i-th OTT and the ISP can be computed as follows

$$R_i^x = \sum_{j=1}^{J} N_{i,j}^x \cdot P_{i,j} \tag{4.1}$$

where $i = 1, 2, 3, ..., I$ indexes the OTTs collaborating with the ISP and $N_{i,j}^x$ is the total number of users belonging to the j-th class calculated at time t_x for the i-th OTT service. $P_{i,j}$ is the price to be paid for subscribing to the j-th class of service of the i-th OTT application. Accordingly, the total revenue generated by the collaboration between the ISP and all the OTTs can be calculated as

$$R^x = \sum_{i=1}^{I} R_i^x = \sum_{i=1}^{I} \sum_{j=1}^{J} N_{i,j}^x \cdot P_{i,j} \tag{4.2}$$

The evolution of $N_{i,j}^x$ over the time depends on the churn effect, i.e., the process of users leaving the service. Hence, the users being represented by $N_{i,j}^x$ are the active users of both the i-th OTT and ISP, i.e., the user continuing the services in j-th class. This number then evolves over time due to the churn and due to the activation of new contracts, as follows

$$N_{i,j}^x = N_{i,j}^{x-1} \cdot U_{i,j} + \zeta_{i,j} \tag{4.3}$$

where $U_{i,j}$ is the user churn function that is defined in the next section, and $\zeta_{i,j}$ is the number of users joining the j-th class of collaborative service of i-th OTT through advertisement. Indeed, studies conducted in [130] emphasis that mostly the companies gain their customers by effective marketing/advertisement campaigns, which is something considered but not controlled by the proposed modelling. Specifically, the study in [131] emphasized that the Poisson distribution can be utilized to predict the increase in the market share in telecommunication. Hence, $\zeta_{i,j}$ is considered as a stochastic process which follows a Poisson distribution depending upon marketing strategies, socio-economic factors and product discounts.

Churn modelling

The user satisfaction to a service plays an important role in the reputation of any service provider in the market. Lowering the level of user satisfaction may result into high level of user churn, i.e., reduction of the number $N_{i,j}^x$ of active users. Notwithstanding the importance of this phenomenon, only limited works exist about the study of the impact of QoE on the user churn. One major obstacle is that to predict/model user churn in terms of QoE requires data over long periods of observation from both OTT and ISP. Still, to go ahead with the proposed analysis, it is considered that there is a high cross-correlation between user satisfaction and user churn. Accordingly, a user churn function based on the Sigmoid function [132] has been built. Indeed, it is one of the mostly used activation function in Multi-layered Perceptron Neural Networks in the field of artificial intelligence to model human perception into machine [133, 134]. The user churn function is considered as upward criterion function, i.e., the function increases with the increase in QoE, which means that more users will be continuing the service if higher QoE is provided, and vice versa. The user churn function can be defined mathematically in terms of QoE as follows

$$U_{i,j}(QoE_{i,j}) = \frac{1}{1 + e^{-z(QoE_{i,j} - QoE^m_{i,j})}} \tag{4.4}$$

where $QoE_{i,j}$ is the quality delivered to the j-th class of service of the i-th OTT service, whereas $QoE^m_{i,j}$ is the quality level at which half of the paying users leave the service in the class j (i.e., $U_{i,j}(QoE^m_{i,j}) = 0.5$). Moreover, the sensitivity of the users with regard to the price paid is represented by z. In fact, users who pay more expect to receive a better quality than those who pay less, and the users keeping the service for the former class of service must be lower than that of the latter, for the same value of QoE perceived. Hence, the higher the price paid the smaller the z, i.e., higher the sensitivity of the user with the quality. The user churn function ranges in the interval $[0, 1]$ where 1 means that the 100% of the users are keeping the service. The QoE is measured as for the MOS in the interval $[1, 5]$ where 1 means minimum quality and 5 maximum quality.

Figure 4.2 shows an example of the user churn function for different values of $QoE^m_{i,j}$ and z. In the Figure, there are two different groups of curves: the continuous curves refer to the lower class of service whose users have lower QoE expectations and for this reason, although the perceived QoE is 2.5, half of the users will be keeping the service. On the other hand, dotted curves refer to the higher class of service, whose users are paying more and therefore have higher QoE expectations. In fact, in this case half of the users will be keeping the service for a MOS at least of 4, which means that half of users for being satisfied and keeping the service expect a more than good QoE. The different values of z identifies the different sensitivity of the users and depends on the price paid to be subscribed to that class of service.

Revenue maximization

With the complete modelling of the revenue, the target of its maximization with a coordinated control of OTTs and ISP can be achieved. Specifically, they target the maximization of an aver-

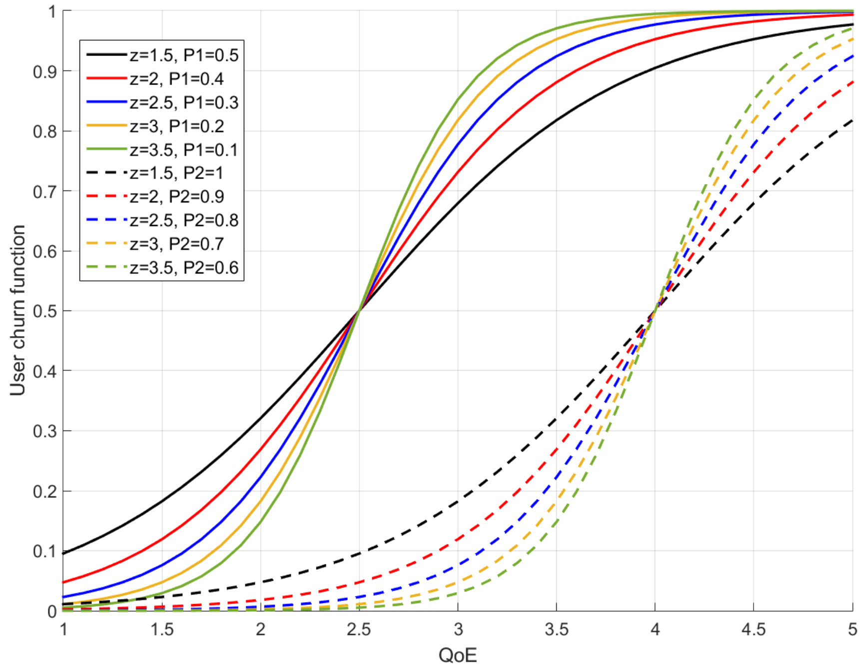

Figure 4.2: User churn function for different values of $QoE^m_{i,j}$ and z. Continuous curves refer to $QoE^m_{i,1} = 2.5$ whereas dotted curves refer to $QoE^m_{i,2} = 4$.

age revenue computed during a reference period $t_{X_1} - t_{X_2}$ as follows

$$\bar{R}^* = \max_{QoE_{i,j}, P_{i,j}} \left[\sum_{x=X_1}^{X_2} \left(\frac{\sum_{i=1}^{I} (\sum_{j=1}^{J} (N_{i,j}^{x-1} \cdot U_{i,j} + \zeta_{i,j}) \cdot P_{i,j}}{t_{X_2} - t_{X_1}} \right) \right] \tag{4.5}$$

where the influence of $QoE_{i,j}$ is taken into account by the user churn function $U_{i,j}$. Even if not explicitly highlighted here, the different combinations of the $QoE_{i,j}$ need to be considered under the available network resources. Then, the collaboration between the OTT and the ISP is fundamental for delivering adequate QoE to the users. The OTT is able to know QoE expectations of the user and to measure the QoE delivered, while the ISP supports the OTT by providing the needed network services. The output of this maximization are the $QoE^*_{i,j}$ levels and prices $P^*_{i,j}$ for the different service classes. This maximization will be done at the ISP side in order to assure better quality to the end users in accordance with the reference architecture provided in Section 4.1.1, whereas through the interface defined between the OTTs and the ISP the maximization results can be shared with the respective OTTs involved in collaboration.

How the OTT and the ISP decide to divide the revenue is out of the scope of this study. However, a joint venture approach can be considered for the revenue sharing where an involved enterprise can get the share of revenue proportional to the amount of investment made by that enterprise over the total amount of investment for the service delivery. For an ISP, the investment may occur in the form of maintenance, upgradation and operations of the access/core network infrastructure, while an OTT can make investment in specialized data centers, multimedia streaming servers, content delivery networks and data-center networks. Additionally, it is important to note that this approach can be implemented without violating the Network Neutrality principle in several ways: better QoS could be provided by hosting OTT content in ISP nodes and using underutilized network areas without affecting the other OTTs' traffic; traffic could be prioritized if it does not affect the final QoE of the applications of which the traffic flows could be delayed.

4.1.3 Simulation

The objective of the conduced simulations is an analysis of the potential of the proposed collaboration approach. Specifically, an ISP and 2 OTTs are considered, and their revenue generation is investigated for two different approaches: No Collaboration (NC) and Joint Venture (JV). The former does not consider a collaboration between the OTTs and the ISP so that the OTTs deliver their contents through the best effort service over the ISP network. The JV is the collaboration approach described in Sections 4.1.1 and 4.1.2, i.e., the OTTs collaborate with the ISP with the objective of maximizing the revenue. Without loss of generality, two specific OTT services were considered: video streaming and VoIP. The reason for the selection of these applications is in accordance with the studies conducted in [135, 136] that considered video streaming and VoIP as the most sensitive multimedia applications with reference to network resources usage.

QoE models

For the evaluation of the QoE of the video streaming service, the model proposed in [38] has been considered, i.e., a parametric packet-layer model for monitoring the video quality of IPTV services, which measures the QoE provided by HD (1440×1080) videos encoded with the H.264 codec at different bitrates and corrupted by packet loss:

$$QoE_{video}^{HD} = 1 + \left(v_1 - \frac{v_1}{1 + \left(\frac{BR}{v_2}\right)^{v_3}} \right) \exp\left(-\frac{PLR}{v_4} \right) \tag{4.6}$$

where $v_1 = 3.8$, $v_2 = 4.9$, $v_3 = 3.6$ and $v_4 = 3.5$ are the coefficients of the model while BR and PLR are the source coding rate of the video and the packet loss rate of the network, respectively. This model has been selected for evaluating the QoE provided by HD videos because it considers both application (source coding rate) and network (PLR) parameters and because the cross-correlation factor computed between the proposed model and subjective QoE results is greater than 0.9 with 99% confidence interval.

In [39], the authors extended the model in [38] considering also the movement of the video content, the MPEG-2 codec and different video resolutions. The model is as follows:

$$V_q = 1 + 4K\left(1 - \frac{1}{1 + \left(\frac{b \cdot BR}{v_5}\right)^{v_6}}\right) \tag{4.7}$$

$$K = 1 + k_1 \exp(-k_2 \cdot b \cdot BR) \tag{4.8}$$

where, for videos with medium content movement, encoded with the H.264 codec at SD resolution, $v_5 = 0.67$, $v_6 = 1.4$, $b = 1$, $k_1 = 1.36$ and $k_2 = 1.93$. Also the model in Eq. (4.7) can take into account the effect of the PLR if multiplied for the exponential factor of Eq. (4.6). Therefore, the model in Eq. (4.9) is considered for evaluating the QoE provided by SD videos:

$$QoE_{video}^{SD} = 1 + 4K\left(1 - \frac{1}{1 + \left(\frac{BR}{v_5}\right)^{v_6}}\right) \exp\left(-\frac{PLR}{v_4}\right) \tag{4.9}$$

Both the models in Eqs. (4.6) and (4.9) measure the QoE with values ranging from 1 (Bad quality) to 5 (Excellent quality) as the MOS.

For the evaluation of the QoE of the VoIP service, the E-Model is selected [137]. The E-model is a planning parametric model defined by the ITU for VoIP applications, which measures the voice quality in terms of the R-factor, i.e., a quality index ranging from 0 to 100, where 100 is the best quality. The R-factor is defined in terms of several parameters as follows

$$R = 100 - I_s - I_d - I_{ef} + A \tag{4.10}$$

where I_s is the signal-to-noise impairment, I_d is the impairment associated to the mouth-to-ear delay of the path, I_{ef} is the equipment impairment associated with the losses within the codecs and A is the advantage factor which allows for compensation of impairment factors when the user benefits from other types of access to the user. The study in [138] presented an adapted version of the E-Model (see Eq. (4.11)), which emphasizes the effect of sources of quality degradation observed over data networks, namely one-way delay, packet loss ratio, and coding scheme. The adapted model is

$$R = 94.2 - I_d(d) - I_e(CODEC, PLR) + A \tag{4.11}$$

where I_d and I_e capture the quality degradation caused by delay and equipment impairment factors, respectively. d is the mean one-way delay of played voice packets during an assessment interval, PLR is the packet loss ratio, and $CODEC$ is the used speech encoding scheme.

The quality degradation caused by one-way delay when echoes are perfectly removed are calculated as

$$I_d(d) = 0.024 \cdot d + 0.11 \cdot (d - 177.3) \cdot H(d - 177.3) \tag{4.12}$$

where

$$H(x) = \begin{cases} 1, & x < 0 \\ 0, & x \geq 0 \end{cases} \quad (4.13)$$

On the other hand, the quality degradation caused by equipment impairment factors are calculated as

$$I_e(CODEC, PLR) = a_1 + a_2 \cdot ln(1 + a_3 \cdot PLR) \quad (4.14)$$

where a_1, a_2 and a_3 are coefficients obtained through a logarithmic regression analysis depending on the used speech codec. For example, for the G.729a codec $a_1 = 11, a_2 = 40$ and $a_3 = 10$ whereas for the G.711 codec $a_1 = 0, a_2 = 30$ and $a_3 = 15$.

With regard to the advantage factor, the default value of A in case of conventional wirebound communication system is $A = 0$. The maximum values of A are provided in [137] for different scenarios. For example, $A_{MAX} = 5$ in case of mobility by cellular networks in a building and $A_{MAX} = 10$ in case of mobility in a geographical area or moving in a vehicle.

Furthermore, in [138] is also provided an equation for converting the R-factor with values between 1 and 5 as the MOS:

$$QoE_{VoIP} = \begin{cases} 1, & R < 0 \\ 4.5, & R > 100 \\ 1 + 0.035R + 7 \cdot 10^{-6}R(R-60)(100-R), & 0 < R < 100 \end{cases} \quad (4.15)$$

The model in Eq. (4.15) is considered for evaluating the QoE provided by the VoIP application, where R is computed with Eq. (4.11).

Simulation results

The simulation scenario considers two OTT applications which are delivered to their users through a network owned by an ISP. For simplicity, it is assumed that the users are stationary and located in the same area, where the Internet access is provided by the ISP. For both the approaches (NC and JV) and for both the applications (video streaming and VoIP), the users can choose between two different plans: standard plan (service class 1) at price $P_{i,1}$ and premium plan (service class 2) at price $P_{i,2}$, with $P_{i,1} < P_{i,2}$. The subscript i identifies the OTT application. Normalized prices are considered so that $P_{i,1}, P_{i,2} \in [0, 1]$. Each user subscribes to one of the two proposed plans on the basis of his/her willingness to pay $W^n_{i,j}$, where n indexes the user. It is assumed that the user is at least a standard user, then $W^n_{i,j} \in [P_{i,1}, 1]$. As a consequence, if $P_{i,1} \leq W^n_{i,j} < P_{i,2}$ the user is a standard user, while if $W^n_{i,j} \geq P_{i,2}$ the user is a premium user. Therefore, for the application i, there will be $N_{i,1}$ users subscribed to the standard plan and $N_{i,2}$ users subscribed to the premium plan, while the total number of users N_i

will be $N_i = N_{i,1} + N_{i,2}$.

On the application side, with regard to the video streaming application, standard users can watch videos only at standard quality (SD), i.e., with a resolution of 720×480 pixels, whereas premium users can watch videos at HD quality, i.e., with a resolution of 1440×900 pixels. On the other hand, both standard and premium VoIP users have access to standard VoIP services (calls, phone conferencing, etc.) whereas only premium users can have access to extra services such as recording functions, voicemail, etc. For VoIP simulations the G.729 codec is considered, because it provides good performance and requires a low bandwidth (31.2 kbps [139]).

On the network side, there is a difference between the NC and JV approaches. In fact, while for the NC approach the applications are delivered on the best effort network, for the JV approach the ISP provides different network resources to the standard and premium users of the applications. Specifically, for the video streaming application, a minimum bandwidth of 2 Mbps and 5 Mbps is guaranteed to standard and premium users, respectively. In fact, generally a HD video is encoded at a bitrate ranging from 1.5 Mbps to 4 Mbps whereas a SD video is encoded at a bitrate ranging from 500 kbps to 2 Mbps [140]. Furthermore, a PLR lower than 0.3% is guaranteed to premium users whereas for standard users the maximum PLR will be 1.5%. These PLR values are selected on the basis of the study in [38], where the influence of the PLR on the QoE for video streaming has been investigated. With regard to the VoIP application, on the basis of the study in [138], a one-way delay lower than 100 ms and a PLR lower than 1% are guaranteed to premium users whereas for standard users the maximum one-way delay and PLR will be 350 ms and 5%, respectively. As discussed in Section 4.1.2, the quality of the service classes is expressed in terms of ELA and therefore it is assumed that with these network and application parameters the JV approach can provide at least a quality of 3 (Fair quality) to standard users and of 4 (Good quality) to premium users. For the NC approach, the total bandwidth is divided in equal parts to each user with no guarantee of minimum bandwidth provided. Furthermore, for PLR and delay the same maximum values selected for the standard users of the JV approach are considered.

Simulations were conducted with the Matlab software setting a starting number of users $N_{VoIP} = N_{Video} = 100$ and considering a total bandwidth of 500 Mbps. Since the PMP pricing model is used, $P_{i,1}$ ranges from 0.1 to 0.5 while $P_{i,2}$ ranges from 0.6 to 1.0, with a step of 0.1 [141]. It is assumed that $P_{VoIP,1} = P_{Video,1}$ and $P_{VoIP,2} = P_{Video,2}$. For each combination of the prices $P_{i,1}$ and $P_{i,2}$, a willingness to pay is randomly assigned (uniform distribution between 0 and 1) to each user and on the basis of this value the user is assigned to the standard or premium classes of the VoIP and video streaming applications. For simplicity, it is assumed that the willingness to pay is uniformly distributed between 0 and 1. This way, the higher the

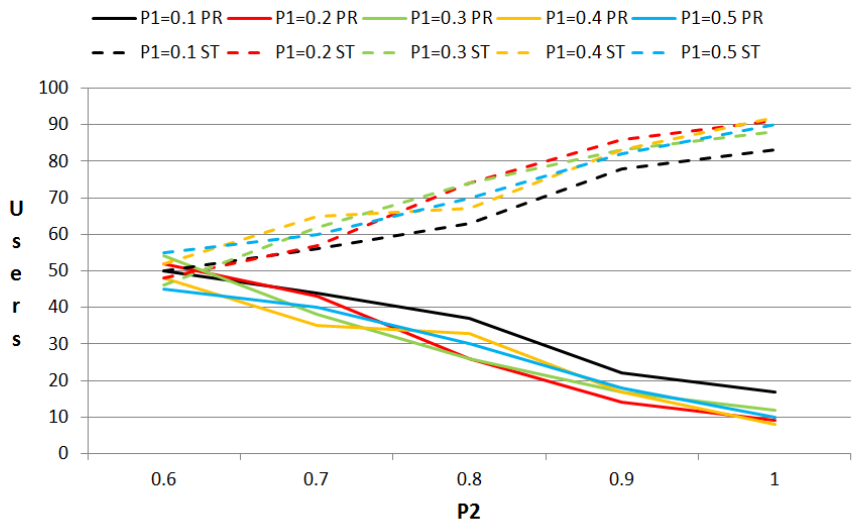

Figure 4.3: Number of starting users for standard (ST) and premium (PR) classes of service as a function of the prices $P_{i,1}$ and $P_{i,2}$.

price for joining the class of service the lower the number of users joining that class. As an example, Figure 4.3 shows the starting number of users in function of the prices $P_{i,1}$ and $P_{i,2}$. For example, within the population of 100 users, fewer users will join the premium class and more user will join the standard class as $P_{i,2}$ approaches 1. However, the willingness to pay distribution only influences the starting number of users joining the classes of service while the number of users keeping or leaving the service in next months depend on the user churn model based on the user's QoE. Therefore, it is expected that using different willingness to pay distributions will bring to the same revenue results in the long period.

Once the starting number of users for each class of service are assigned, the starting video and VoIP revenue is computed with Eq. (4.2). The objective is to investigate the revenue of the 2 OTTs for the following 24 months by using Eq. (4.5) for the revenue maximization and the QoE models discussed in the previous section for the QoE evaluation. With regard to $U_{i,j}$, $QoE^m_{i,1} = 2.5$ for the standard service and $QoE^m_{i,2} = 4$ for the premium service, since premium users have greater QoE expectations than standard users. Figure 4.2 shows the user churn function for different values of z and $QoE^m_{i,j}$. With regard to $\zeta^x_{i,j}$, it is computed as a random number from the Poisson distribution with the mean equal to the 5% of users belonging to the j-th class and application i at time $(x - 1)$. The time range x in this case is a month. Within each month, 100 QoE measurements are computed and the resulting average QoE is used for maximizing the revenue in Eq. (4.5).

Figures 4.4, 4.5 and 4.6 show the revenue obtained with the two approaches by the two OTTs in the first 2 years as a function of the prices $P_{i,1}$ and $P_{i,2}$. The most evident result is that for each prices combination the revenue obtained with the JV approach is always greater than that obtained with the NC approach for both the video and VoIP applications. This is mainly due

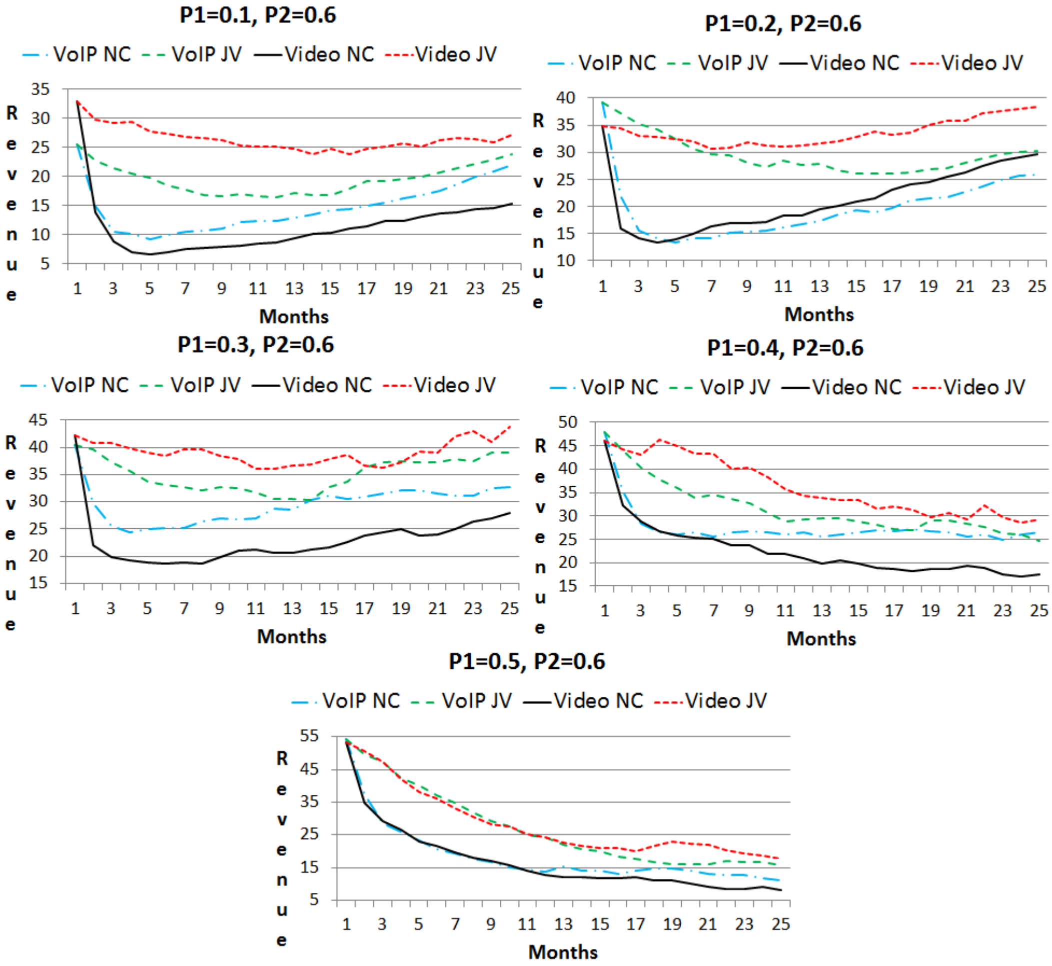

Figure 4.4: Revenue obtained with the two approaches by the two OTTs in the first 2 years varying $P_{i,1}$ from 0.1 to 0.5 and with $P_{i,2} = 0.6$.

to the fact that with the JV approach the OTTs collaborating with the ISP are able to satisfy the QoE expectations of both the standard and premium users. Specifically, the premium users are those who contribute to the revenue difference between the two approaches. In fact, standard users are less QoE demanding and they are the main contributors to the revenue generation in the case of the NC approach. Indeed, from the graphs, it is evident that when the price for the premium service is accessible to many users ($P_{i,2} = 0.6$ and $P_{i,2} = 0.8$), the NC approach fails to satisfy premium users, resulting in a great revenue drop, which is balanced over the time only thanks to the revenue provided by the standard users. When the price for the premium service reaches the highest value (i.e., $P_{i,2} = 1.0$), the standard users are prevalent with respect to the premium users and the difference between the two approaches is less evident although the JV approach provides quite higher revenue for both the applications.

From Figures 4.4-4.6, it can also be noticed another interesting result concerning the z parameter, which represents the sensitivity of the user to the price, as shown in Figure 4.2. In fact, with the increasing of $P_{i,1}$, the standard users become more QoE demanding and are

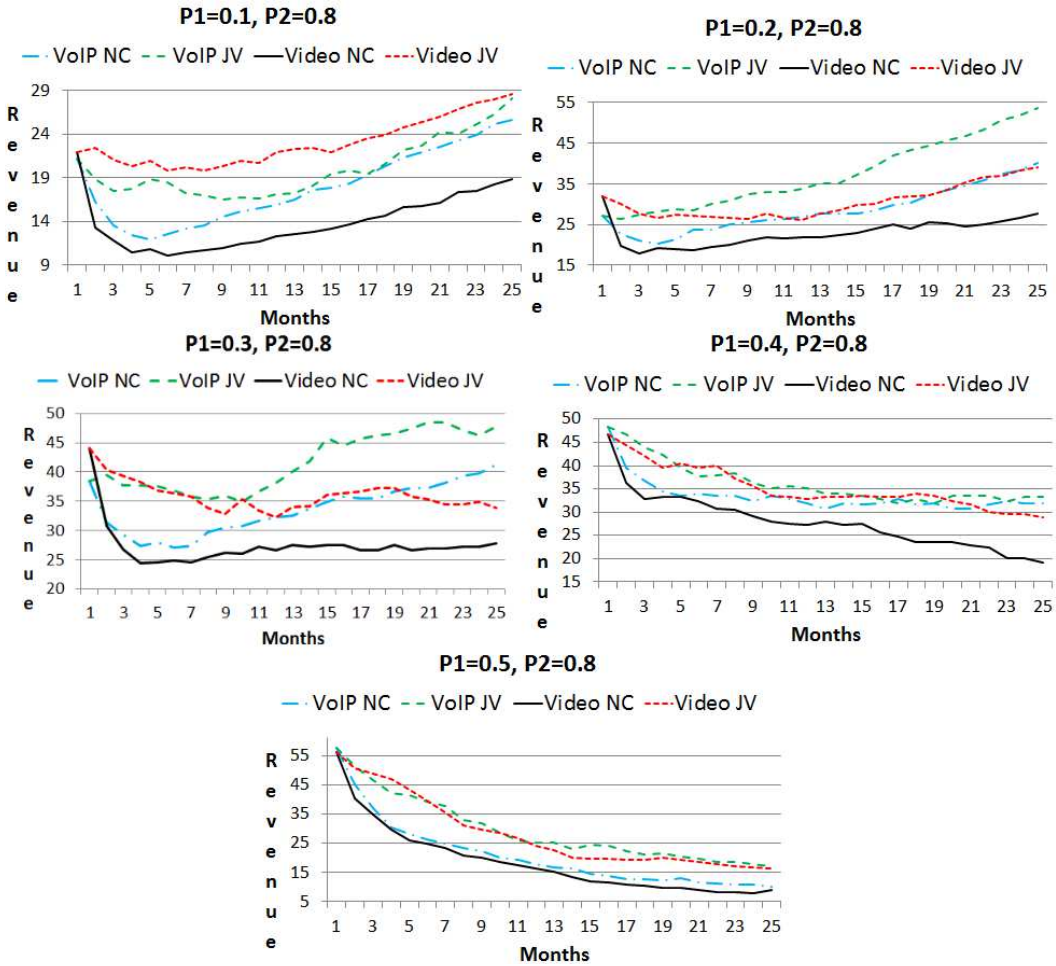

Figure 4.5: Revenue obtained with the two approaches by the two OTTs in the first 2 years varying $P_{i,1}$ from 0.1 to 0.5 and with $P_{i,2} = 0.8$.

more likely to leave the service if the QoE provided is not adequate. Indeed, for $P_{i,1} = 0.4$ and $P_{i,1} = 0.5$ the revenue is not more increasing over the time as for the lower values of $P_{i,1}$, but is decreasing because not all the users are satisfied by the quality of the perceived service.

Figure 4.7 shows the QoE provided by the video and VoIP applications for the NC and JV approaches, in terms of the MOS with 95% confidence interval. “ST” and “PR” stand for standard and premium service, respectively. With regard to the VoIP application for the NC approach there is no distinction between standard and premium services because the considered QoE model is a function of the only network parameters and in the case of NC approach the ISP does not guarantee any network parameter to premium users. Then, the same QoE is provided to standard and premium users. The difference between standard and premium users in this case are the extra application features which cannot be evaluated with current QoE models.

The QoE values are the average QoE computed over all the simulation cycles, and the error bars show the minimum and maximum QoE values provided. It is evident that the JV approach is able to provide a great and stable QoE to the premium users of both the applications,

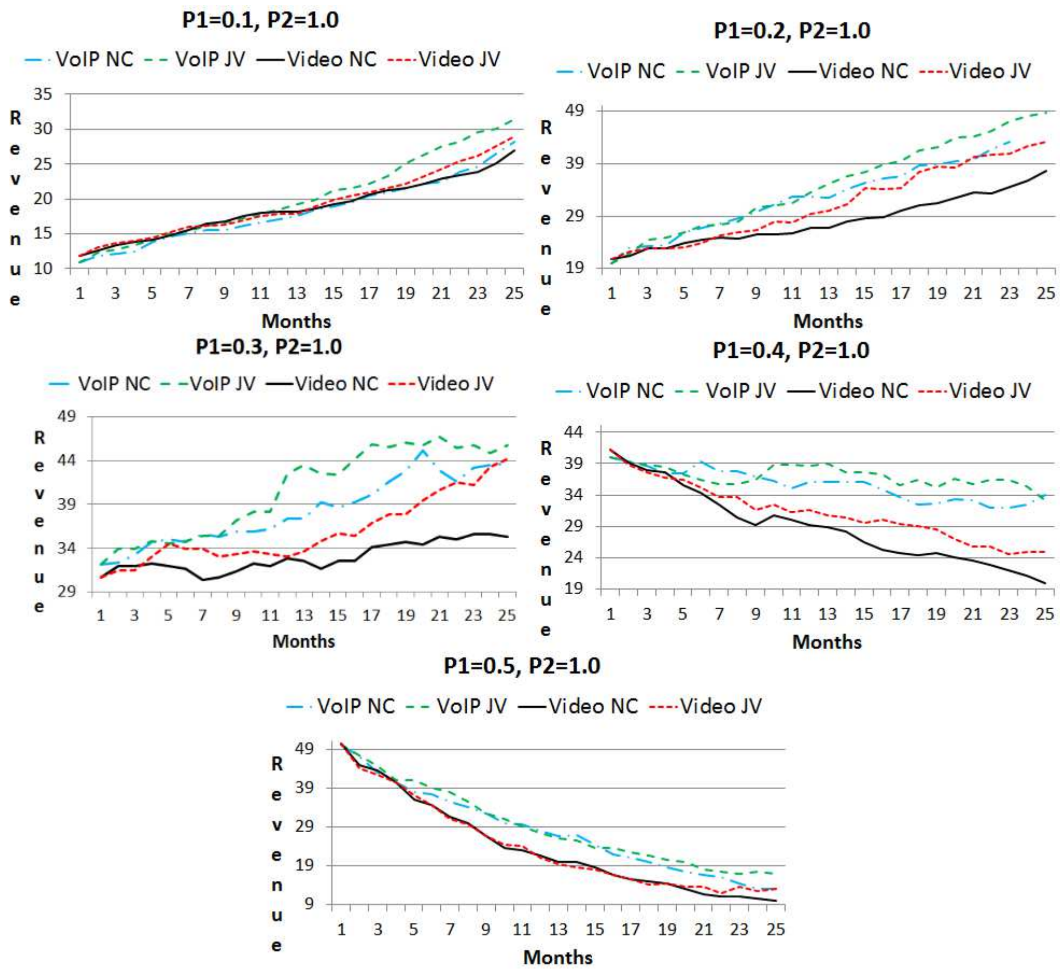

Figure 4.6: Revenue obtained with the two approaches by the two OTTs in the first 2 years varying $P_{i,1}$ from 0.1 to 0.5 and with $P_{i,2} = 1.0$.

which results in a significant revenue generation as discussed before. On the other hand, the NC approach fails in this objective, providing to premium users a QoE even lower than that provided to standard users. With regard to the standard users, the two approaches provide comparable QoE for both the applications.

Concluding, with regard to the JV approach, the best trade-off is obtained for $P_{i,1} = 0.3$ and $P_{i,2} = 0.6$, with a quite constant revenue with an average of 40 and 35 for video and VoIP application, respectively. On the other hand, for the NC approach the most convenient prices are $P_{i,1} = 0.3$ and $P_{i,2} = 1.0$, with an increasing revenue with an average of 35 and 45 for the video and VoIP application, respectively. However, with these prices and considering the low QoE provided to premium users, it does not make any sense to offer two service classes to the users but it would be better to restrict to the only standard service.

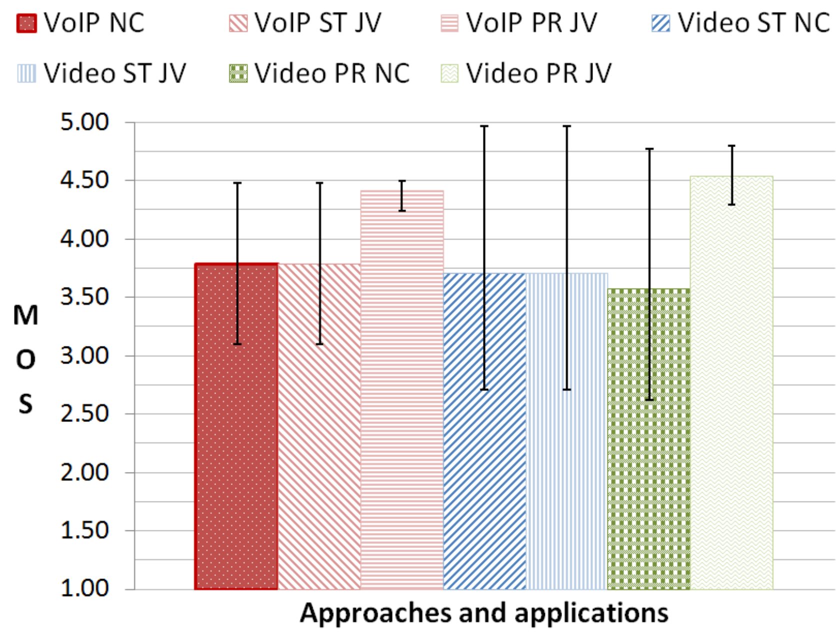

Figure 4.7: QoE provided by the video and VoIP applications for the NC and JV approaches, in terms of the MOS with 95% confidence interval.

4.2 QoE-aware Smart Home Energy Management system

Smart Homes are characterized by the presence of smart devices, which give the opportunity to monitor and to remotely control key equipment within homes with Smart Home Energy Management (SHEM) systems. In such an intelligent environment, one of the major goals is to provide decision-support tools in order to aid users in making cost-effective decisions when utilizing electrical energy. As a matter of fact, nowadays domestic electricity usage accounts for 30% of the global energy consumption and usage awareness and scheduling optimization alone have the potential to reduce consumption by 15% in private households [94]. However, also the quality (i.e. comfort) perceived by final users when policies are put in place is crucial for wide user acceptance and pertains to the domain of QoE.

Therefore, a SHEM system based on profile characterization of the involved users' appliances and a posteriori evaluation of the customer comfort is proposed. The aim is to dynamically shift tasks of controlled appliances to lower the overall energy cost of a household while also exploiting Renewable Energy Sources (RES) [142], in a QoE-aware manner which considers annoyance as a multi-value scale rather than a hard constraint. In Section 4.2.1, the considered reference scenario is presented, i.e., a group of houses such as a block or a condominium, which is defined as Cooperative Neighbourhood. Furthermore, the energy consumption model for controlled appliances is described as well as the system functional model. Section 4.2.2 describes the details of the survey that has been conducted on a population sample of 427 subjects, about the degree of annoyance perceived when the starting time or the set temperature of appliances is modified with respect to users' preferences. The results have been clustered in different profiles using the k-means algorithm. Based on these results and on the created profiles for each appliance, a Smart Home environment has been created where smart appliances can be easily installed and the proper profile for each user is assigned. In Section 4.2.3, the task scheduling model is presented, which relies on two algorithms: the QoE-aware Cost Saving Appliance Scheduling (Q-CSAS) algorithm that is aimed at scheduling controlled loads based on users' profile preferences and Time-of-Use (TOU) electricity prices; and the QoE-aware Renewable Source Power Allocation (Q-RSPA) algorithm that modifies the working schedule of appliances whenever a surplus of energy has been made available by renewable sources. The final objective is that of scheduling the appliances' operations, such as starting time and set temperature, so that a trade-off between energy expenses and annoyance perceived is achieved. Finally, in Section 4.2.4, the performance of the proposed QoE-aware SHEM system are compared with respect to the case of a QoE-unaware system (which only optimizes the starting time with reference to cost saving), in terms of energy cost savings and annoyance rate.

4.2.1 System overview and model

A Smart Home scenario is considered where the aim is to modify the execution of tasks of controlled appliances, so that the electricity costs are reduced and RESs are exploited to their maximum extent while trying to minimize the annoyance perceived by users. Controlled appliances are those whose functioning behaviour can be modified provided that this action can generate cost savings and affects user's QoE within given limits. The reference scenario is that of a group of houses such as a block or a condominium, which is defined as Cooperative Neighbourhood. The rationale behind considering a Cooperative Neighbourhood is that in case the energy produced by RES in a Smart Home in a given moment cannot be partially or entirely used by loads in the same home, this energy is transferred to one of the neighbours according to a consensus algorithm.

Consider Figure 4.8. Inside each house there are appliances that consume and produce energy. On the other hand, power supplies such as the electric grid, solar panels, and micro wind turbines provide energy that can be used to run appliances. Smart Meters and actuators are associated to these appliances to monitor their energy consumption/production and control their activation/deactivation. The appliances are divided into 4 groups, based on their characteristics and requirements:

- **G1:** not controlled loads, i.e., small loads such as lights and smartphone chargers, and not controlled high loads such as freezer and fridge;
- **G2:** switching controlled high loads, e.g., washing machines and clothes dryers;

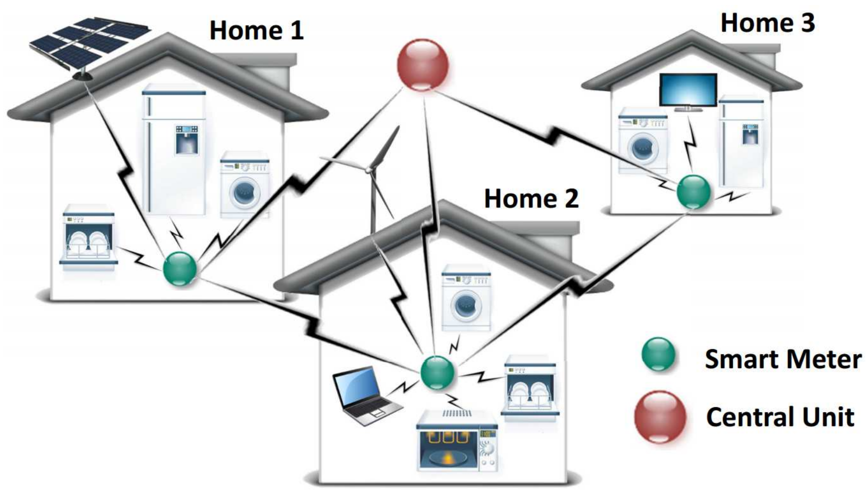

Figure 4.8: Reference scenario

G3: thermostatically controlled high loads, i.e. appliances that are controlled by a thermostat such as Heating Ventilation and Air Conditioning (HVAC) and Water Heaters (WHs);

G4: supplies such as solar panels and micro wind turbines.

Energy consumption model for controlled appliances

The energy consumed by appliance i to complete a given task, E_i^{cons}, is defined as the product between its power consumption P_i^{cons} and the execution time it needs to complete the task t_i^{exec}

$$E_i^{cons} = P_i^{cons} \times t_i^{exec} \tag{4.16}$$

While for switching controlled appliances the execution time is a constant value, for the thermostatically controlled ones it depends on some variable parameters. Considering the outside temperature $T_i^{out}(t)$ at time t (i.e., the temperature measured outside the house for HVAC, and the temperature of cold water for WH), and the inside temperature $T_i^{in}(t)$ at time t (i.e., the temperature measured inside the room for HVAC and the temperature of the water inside the boiler for WH), the inside temperature that is expected after a certain amount of time Δt can be defined as [143, 144]

$$T_i^{in}(t+\Delta t) = -(T_i^{out}(t) + R_i P_i^{heat} - T_i^{in}(t))e^{-\Delta t/R_i C_i} + T_i^{out}(t) + R_i P_i^{heat} \tag{4.17}$$

where P_i^{heat}, R_i and C_i are characteristic parameters for the appliance: P_i^{heat} is the heat rate (in Watt), R_i is the equivalent thermal resistance (°C/Watt) and C_i is the equivalent heat capacity (Joule/°C). If the appliance is off, $P_i^{heat} = 0$.

After some simple computations, $\Delta t = t_i^{exec}$ is the time that is needed to take the inside temperature to an arbitrary amount T_i^{exp} as

$$t_i^{exec}\left(T_i^{exp}\right) = -R_i C_i \ln\left(\frac{T_i^{out}(t) - T_i^{exp} + R_i P_i^{heat}}{T_i^{out}(t) - T_i^{in}(t) + R_i P_i^{heat}}\right) \tag{4.18}$$

System functional model

At first, when a new appliance is plugged in a Home Area Network (HAN), information related to appliance's characteristics and tasks it is able to perform will be detected by Smart Meters and sent to a *Central Unit* that connects all neighbourhood's households. Users' habits and preferences on appliance usage are also registered over a training period of few days or weeks (depending on the appliance), in which few simple questions about annoyance due to task shifting for G2 and G3 appliances are asked to the user at the end of usage or at the end of the week. Notice that, these questions are asked only on the first days in which new appliances are installed and will not be asked again if the same usage has already been registered. Based on these answers, a user appliances' usage profile is associated to the appliance, according to the clusters that will be presented in Section 4.2.2, and sent to the Central Unit as well. If customers do not answer any question over an extended period, they are profiled as customers which are not willing to save money using the proposed system. The survey in the next section takes into account also this kind of profile. As a consequence, users falling into this category will not benefit from cost savings differently from the customers who actively participate, thus indicating a certain flexibility on appliances' usage. This information is used as input to the algorithms composing the SHEM system, which will decide the best scheduling for each controlled appliance based on the metrics presented in Section 4.2.3.

Consider the appliances (or energy sources) in the entire Cooperative Neighbourhood indexed with $i \in \{1, 2, \ldots, I\}$ and the homes indexed with $h \in \{1, 2, \ldots, H\}$. Each house's smart meter, namely SM_h, stores the key parameters about appliance i, depending on which Group it belongs to, as illustrated in Table 4.1.

4.2.2 QoE-driven appliance's usage profile

For any appliance, a QoE-driven usage profile must be defined. To this a survey has been conducted, whose collected data has been processed to obtain different profiles. These are then used to select the best one for each used appliance when the proposed algorithm is in use. These aspects are described in the following subsections.

Table 4.1: Key parameters about appliance i for each Group of appliances.

Type	Parameter	Description
G1	G_h^1	Set of appliances of G1 for home h
	$x_i(t)$	State (on/off) for appliance i at time t
	P_i^{cons}	Power consumed by appliance i
	$Pr_i(t)$	Probability that appliance i performs its task at time t
G2	G_h^2	Set of appliances of G2 for home h
	$x_i(t)$	State (on/off) for appliance i at time t
	P_i^{cons}	Power consumed by appliance i
	t_i^{exec}	Time needed by appliance i to perform its task (fixed time)
	t_i^{PT}	User's preferred time for the task of appliance i
	$\hat{\mathbf{Q}}_i$	QoE profile for appliance i, as explained in Section 4.2.2
	t_i^{ST}	Time when i started its current task
G3	G_h^3	Set of appliances of G3 for home h
	$x_i(t)$	State (on/off) for appliance i at time t
	P_i^{cons}	Power consumed by appliance i
	t_i^{exec}	Time needed by appliance i as defined in Eq. (4.18)
	T_i^{PT}	User's preferred temperature for the task of appliance i
	$\hat{\mathbf{Q}}_i$	QoE profile for appliance i, as explained in Section 4.2.2
	$T_i^{in}(t)$	Inside temperature of appliance i at time t (see Section 4.2.1)
	$T_i^{out}(t)$	Outside temperature of appliance i at time t (see Section 4.2.1)
G4	G_h^4	Set of RES of G4 for home h
	$x_i(t)$	State (on/off) for RES i at time t
	P_i^{prod}	Power produced by RES i at time t
	$Pr_i(t)$	Probability that RES i has power to deliver at time t

Conducted survey

As discussed in Section 2.1.1, the QoE is defined as *"the degree of delight or annoyance of the user of an application or service."* [6]. Typically, the QoE is evaluated conducting a subjective quality assessment in which a group of subjects taking part to the tests have to rate the quality of an application or a service on the basis of their quality perception. Following this principle, in this work people preferences are investigated by asking the subjects to complete a survey in which they had to indicate their preferences with regard to the utilization of controlled home appliances. As introduced in Section 4.2.1, controlled high loads are divided in switching controlled high loads (belonging to group G2) and thermostatically controlled high loads (belonging to group G3). Also in the survey these two categories of appliances are distinguished because their utilization is different. In fact, while for the former the user is interested in the starting time, for the latter the most important factor is the working temperature, independently from the starting time. Accordingly, in the survey the subjects are asked to indicate the degree of annoyance perceived when the preferred starting time (for G2) or set temperature (for G3) was changed. From the survey results it is expected to find similar preferences provided by different users in order to create specific usage profiles for each appliance.

The survey was conducted online and it was spread to the greatest possible number of contacts of the authors and colleagues. In total, the survey was completed by 427 subjects. It consisted in some web pages in which the subjects were asked to answer some questions about their personal information and their appliances usage habits. Specifically, in the first page of the survey the instructions for compiling the survey were provided. In the second page, personal information about the user were asked: sex, age, profession, days off and working days in a whole week, number of people living in the house and when the users were in the house (morning, afternoon, evening, night). This information is useful for understanding whether appliances usage habits could be related to some personal data of the subjects (age, profession, etc.). As a result, appliances usage habits were collected from a heterogeneous pool of subjects. Indeed, their age was ranging from 18 to 72 year old; their job fell mostly within the categories of student, employee, freelance and homemaker; they were living alone or with a number of people ranging from 1 to 7; there were subjects working in different time periods, included night jobs. At the end, the subjects that participated to the survey covered quite different customers behaviors. For the scenario of multimedia services, recommendations for performing the assessment of the user perceived quality indicate that the number of subjects should be at least 15 and should possibly reach 40 [34]. This is valid for tests conducted in laboratory as well as online [145]. Herein different services are considered, but having exceeded these reference numbers is believed to be a positive feature. However, to collect a greater number of user' opinions assuring users heterogeneity and randomness, providers of online survey tools, such as Qualtrics, SurveyMonkey, SurveyGizmo, could be used. These allow to create an online survey and to spread the survey to a huge number of people. Moreover, a specific target audience can be selected, to get opinions from a certain set of people while assuring user heterogeneity and randomness. An additional online service which helps in spreading online surveys to many people is Prolific. Although Prolific does not provide a service for survey creation, it can be easily integrated with most of the aforementioned online survey platforms. In this case, the survey is already created and could be loaded into the Prolific platform to be spread to a huge number of people, whose characteristics can be precisely selected.

Once this information was provided, each of the remaining pages of the survey was dedicated to a specific appliance, namely: washing machine (WM), dishwasher (DW), clothes dryer (CD), and electric oven (EO) as switching controlled high loads (i.e., category G2); heating ventilation and air conditioning (HVAC) and water heater (WH) as thermostatically controlled

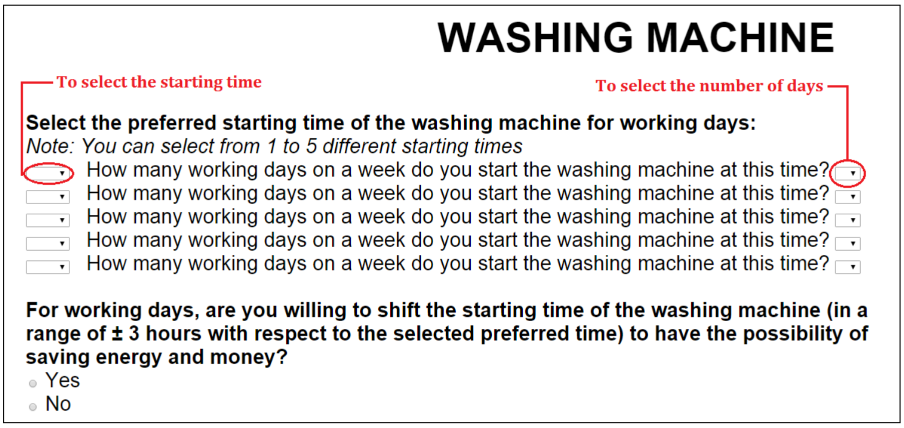

Figure 4.9: Part of the survey page of the washing machine in which the users can select the preferred starting times for working days.

high loads (i.e., category G3). For each switching controlled appliance, the users could select up to 5 preferred times in which they usually started using it. Furthermore, they were asked if they were willing to anticipate or postpone the selected preferred starting time for energy bill saving. For each thermostatically controlled appliance the users had to select their preferred set temperature and they were asked if they were willing to change this temperature value for energy bill saving. For both G2 and G3 appliances, these questions could be answered separately for days off (DO) and working days (WD), since users may have different habits in the two cases. For these reasons, the profiles had to be created for 12 types of combinations appliance/period of the week.

Figure 4.9 shows a part of the survey page of the washing machine in which the users could select the preferred starting times for WD. If the users selected they were willing to anticipate or postpone the preferred starting time (set temperature) of the switching (thermostatically) controlled appliance, a pop up page appeared in which users were asked to rate the annoyance (in a scale ranging from 1 to 5, where 1 is the minimum annoyance and 5 the maximum annoyance) caused by the modification of the preferred starting time or set temperature. The starting time could vary within a range of $\pm$ 3 hours with a step of half an hour, for a total of 13 choices. With regard to the set temperature, according to the different characteristics of these two types of appliances, two dissimilar ranges were considered for HVAC and WH. The set temperature for HVAC could vary within a range of $\pm$ 3 $°C$ with a step of 0.5 $°C$, for a total of 13 choices. The set temperature for WH could vary within a range of $\pm$ 18 $°C$ with a step of 3 $°C$, for a total of 13 choices. Figure 4.10 shows the pop up page in which the users could select their saving preferences for switching controlled appliances. In rating their annoyance level, the users were reminded about the possibility of saving money if the appliance's starting time (set temperature) was shifted. Therefore, inverting the scale, evaluations can also be seen as the user's inclination to save money with respect to a specific appliance in a given day.

SAVING PREFERENCES

For working days, you have selected you are willing to shift the starting time of the appliance to have the possibility of **saving** energy and money. We ask you to complete the following table in which you have to rate the annoyance perceived by the anticipated/postponed starting time of the appliance considering the possibility of saving.

Note: 1 is the minimum annoyance whereas 5 is the maximum annoyance.

Considering the possibility of saving, how much will you be annoyed if, with respect to the selected preferred time, the appliance starts...	1	2	3	4	5
3 hours before?	○	○	○	○	○
2 and a half hours before?	○	○	○	○	○
2 hours before?	○	○	○	○	○
1 and a half hours before?	○	○	○	○	○
1 hour before?	○	○	○	○	○
Half hour before?	○	○	○	○	○
Half hour later?	○	○	○	○	○
1 hour later?	○	○	○	○	○
1 and a half hours later?	○	○	○	○	○
2 hours later?	○	○	○	○	○
2 and a half hours later?	○	○	○	○	○
3 hours later?	○	○	○	○	○

Figure 4.10: Pop up page of the survey in which the users can select their saving preferences for switching controlled appliances.

These shifts in time and temperature are coded into different vectors with a length of 13 elements, as follows

$$\mathbf{S}_t = [-3, -2.5, \cdots, 0, \cdots, +2.5, +3] \tag{4.19}$$

$$\mathbf{S}_T^{HVAC} = [-3, -2.5, \cdots, 0, \cdots, +2.5, +3] \tag{4.20}$$

$$\mathbf{S}_T^{WH} = [-18, -15, \cdots, 0, \cdots, +15, +18] \tag{4.21}$$

where $\mathbf{S}_t$ represents shift times for switching controlled appliances whereas $\mathbf{S}_T^{HVAC}$ and $\mathbf{S}_T^{WH}$ represent shift temperatures for HVAC and WH, respectively.

Annoyance vectors $\mathbf{Q}_{zw}$ of 13 elements are then used to code the survey results as follows

$$\mathbf{Q}_{zw} = [q_{zw}(1), q_{zw}(2), \cdots, q_{zw}(13)] \tag{4.22}$$

where $q_{zw}(y)$ represents the level of annoyance for subject w for the appliance of type z (as said before there are 12 possible combinations of appliance type and period of the week) when the relevant shift in time ($s(y) \in \mathbf{S}_t$) or temperature ($s(y) \in \mathbf{S}_T^{HVAC}$ or $s(y) \in \mathbf{S}_T^{WH}$) is introduced, depending on the category of the appliance. By default $q_{zw}(7) = 1$ (i.e., when no shifting is applied there is no annoyance). On the other hand, if the user is not willing to shift appliance's starting time or set temperature, the value 5 is automatically set for each of the 13 evaluation points, except the preferred time (i.e., $q_{zw}(7)$ is still set to 1).

Creation of profiles

The survey has been completed by 427 people, each of them providing two different evaluations for each of the 6 appliances (DO's user preferences and WDs' user preferences) for a total of 12 different evaluation sets. Since any correlation between users' personal data (age, profession, etc.) and appliances usage habits have not been found, users' profiles were categorized only on the basis of their preferences in modifying the starting time and set temperature of the appliances for DO and WD. Therefore, in order to create user's appliances usage profiles for each of these 12 categories, a clustering algorithm has been used: the k-means algorithm. The k-means algorithm is a widely used clustering technique for partitioning an N-dimensional population into K exclusive clusters [146]. The k-means algorithm treats each sample as a point having a location in space and seeks to minimize the average squared distance between points in the same cluster. Each cluster of data is represented by a centroid, which is the point to which the sum of distances from all points in that cluster is minimized. For clustering the data the Matlab software was used, whose *kmeans* function uses the k-means++ algorithm (an improved version of the k-means algorithm [147]) for cluster center initialization and the squared Euclidean metric to determine distances. Furthermore, to select the optimal number of clusters for each data category, the silhouette value was used [148], which is a measure of how similar each point (annoyance vector of the subject's responses Q_{zw} in our test) is to the others in its cluster, when compared to points in other clusters. The silhouette value for a generic *j*-th point is defined as

$$silhouette(j) = \frac{b(j) - a(j)}{max\{a(j), b(j)\}} \tag{4.23}$$

where $a(j)$ is the average distance from the *j*-th point to the other points in the same cluster whereas $b(j)$ is the minimum average distance from the *j*-th point to points in a different cluster, minimized over clusters. The silhouette value ranges from -1 to +1. A silhouette value close to +1 indicates that j is well-matched to its own cluster and poorly-matched to neighboring clusters. Then, the number of clusters K which provides the highest average silhouette value among all the points of the clusters was selected.

The optimal number of clusters represents the number of different usage profiles for each data category. Note that at the end for any appliance a number of usage profiles $\widehat{\mathbf{Q}}_{zr}$ is obtained, where z still indexes the appliance and r indexes the different usage profiles obtained for each of this. Figures 4.11 and 4.12 show the usage profiles computed for each appliance for WD and DO. These figures also provide the silhouette value obtained by selecting that number of clusters (usage profiles) and the percentage of subjects belonging to each usage profile. It can be noticed that the obtained silhouette values range from 0.725 to 0.930, and are very close to 1. This means that each sample is well-matched with its own cluster. As an example, the graph of the dishwasher for WD is analyzed (from Figure 4.11). The same analysis can straightforwardly

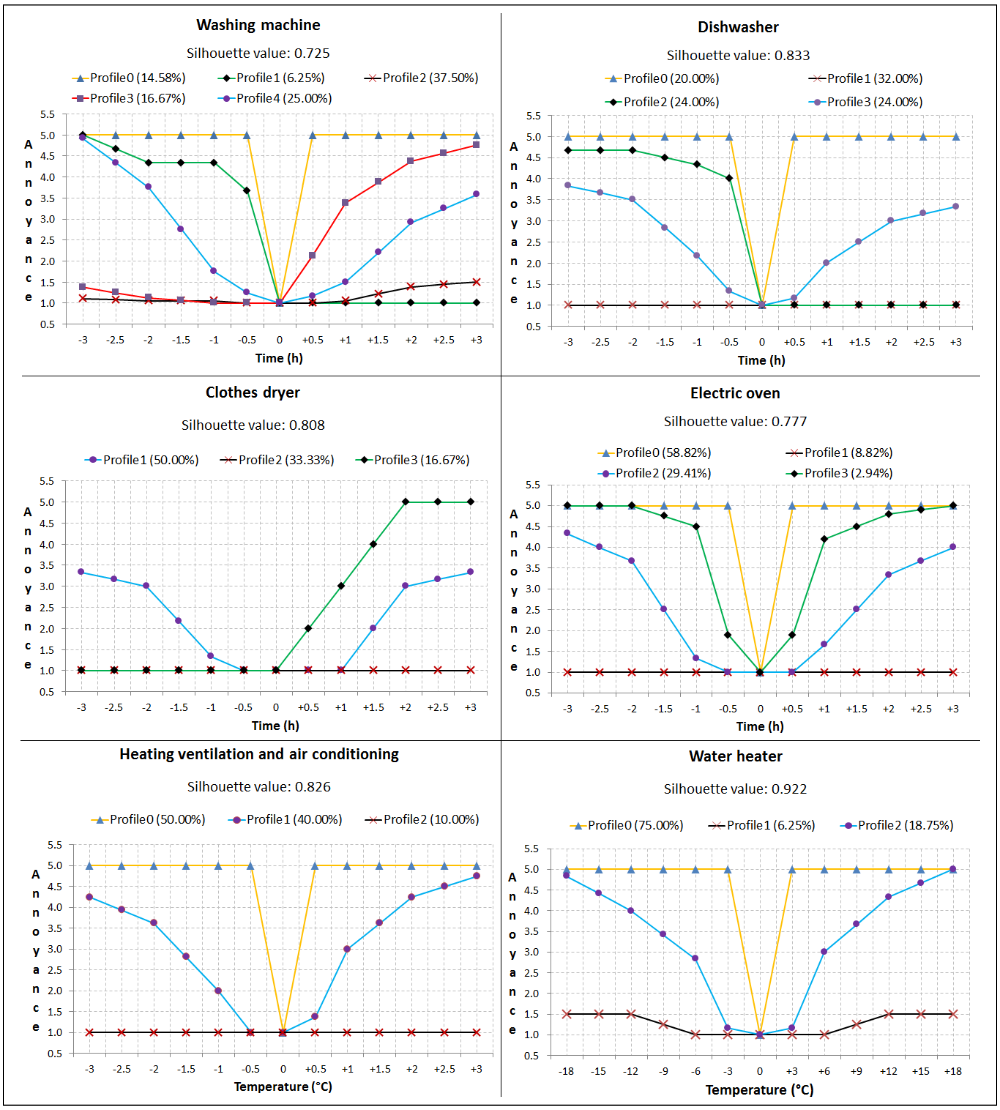

Figure 4.11: Usage profiles computed for each appliance for working days. For each appliance, also the silhouette value obtained by selecting that number of usage profiles and the percentage of users belonging to each usage profile are indicated.

be extended to the other graphs of Figures 4.11 and 4.12. From the evaluation sets provided by the users, the execution of the k-means++ algorithm indicated that 4 is the optimal number of clusters and therefore the optimal number of usage profiles. In fact, it can be noted that each usage profile has a well defined trend with a physical meaning. *Profile0* identifies the users which are not willing to shift dishwasher's starting time at any time. *Profile1* identifies the users which are willing to shift dishwasher's starting time at the whole time range. This profile identifies the users which aims at maximum saving. *Profile2* identifies the users which are willing to postpone, but not to anticipate, dishwasher's starting time. Finally, *Profile3* identifies the users which are willing to shift dishwasher's starting time only at the nearest hours to the preferred time: the largest the shift, the greater the annoyance.

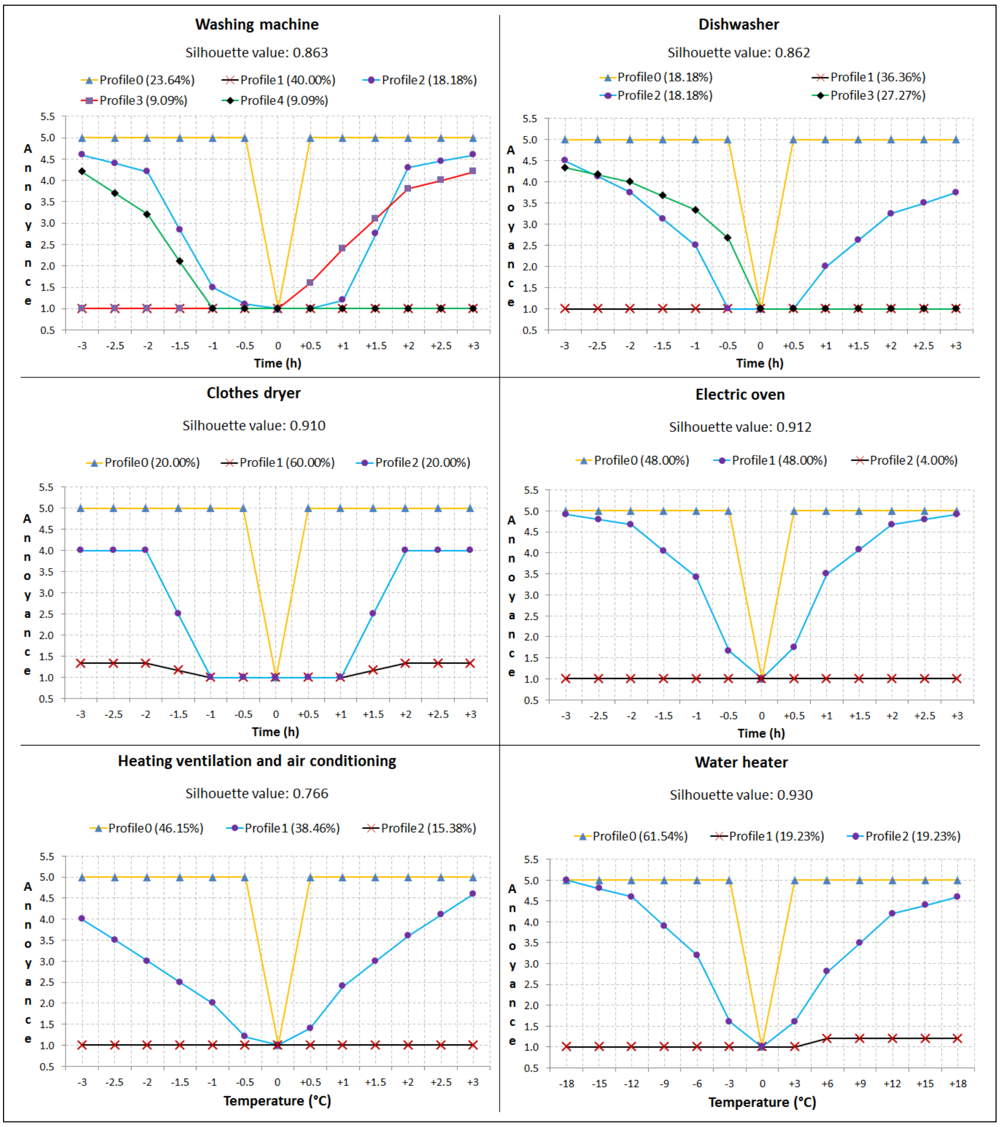

Figure 4.12: Usage profiles computed for each appliance for days off. For each appliance, also the silhouette value obtained by selecting that number of usage profiles and the percentage of users belonging to each usage profile are indicated.

Selection of the appliance's usage profile

The identification of the usage profile to be used for appliance i is done through a training period for new appliances, during which the system registers preferred times of usage and proposes some potential time shifts whenever it is convenient. If time shifts are accepted, the user is asked to rate the perceived annoyance at the end of the task. If the user refuses, maximum annoyance is assumed. The user responses are then processed to select the best profile among the $\hat{\mathbf{Q}}_{zr}$ defined in the previous section. The user responses compose a new annoyance vector for that user and appliance. Then, the silhouette value of this vector is computed with respect to all the clusters (usage profiles) in order to reassign the vector to the best matching profile. This is determined by the highest value of silhouette obtained. If this vector belongs to another usage profile than the one initially assigned, the system changes the user's appliance usage profile accordingly. Once the user's appliance usage profile is assigned, the algorithm works without any further interaction with the user, unless unusual or unexpected usage is revealed with regard to the assigned usage profile (e.g., unusual hours of usage), or if the user proactively wishes to indicate a change on the perceived annoyance based on her experience. In this case, if changes result in a higher silhouette value for another usage profile, the assigned profile is updated accordingly.

When no information is collected to select the best usage profile, the proposed algorithm adopts the one with the highest number of subjects belonging to it for the reference appliance type. In the following, the usage profile selected for appliance i is referred to as $\hat{\mathbf{Q}}_i$.

4.2.3 Task scheduling model

The task scheduling relies on the following two algorithms:

- the QoE-aware Cost Saving Appliance Scheduling (Q-CSAS), which schedules tasks of G2 and G3 appliances in off-peak times;
- the QoE-aware Renewable Source Power Allocation (Q-RSPA), which dynamically shifts tasks in order to maximize the use of RES.

Note that these make use of the usage profile $\hat{\mathbf{Q}}_i$ for each appliance i which is assigned as explained in the previous section. Figure 4.13 illustrates a flow chart which describes the steps of the overall proposed SHEM algorithm.

As soon as appliance i placed in home h needs to start, it sends an activation request to SM_h. If appliance i belongs to G_h^1, i.e., it is not controlled and it is not a supply, it just needs to notify to SM_h that it is changing state ($x_i(t) = 1$) for the whole duration of the task. SM_h sets its probability to be on to 1 accordingly. When appliance i stops, it informs SM_h. Its power consumption and duration values are monitored and sent to the Central Unit, which analyzes them, updates $Pr_i(t)$ accordingly and changes future forecasting if needed.

If the requesting appliance i is a controlled consumer, i.e. it belongs to G_h^2 or G_h^3, Q-CSAS is started. G_h^2 appliances make an activation request as soon as they notice the need for them to start, either because the user requested it or because it has been set in the user profile. Differently, G_h^3 appliances make an activation request when the inside temperature $T^{in}(t)$ reaches a value that corresponds to an annoyance level higher than 1. Q-CSAS is a centralized algorithm that is performed by the SM to assign the starting time t_i^{ST} of controlled appliances, so that their tasks are executed during the most convenient hours, when electricity price is lower, according

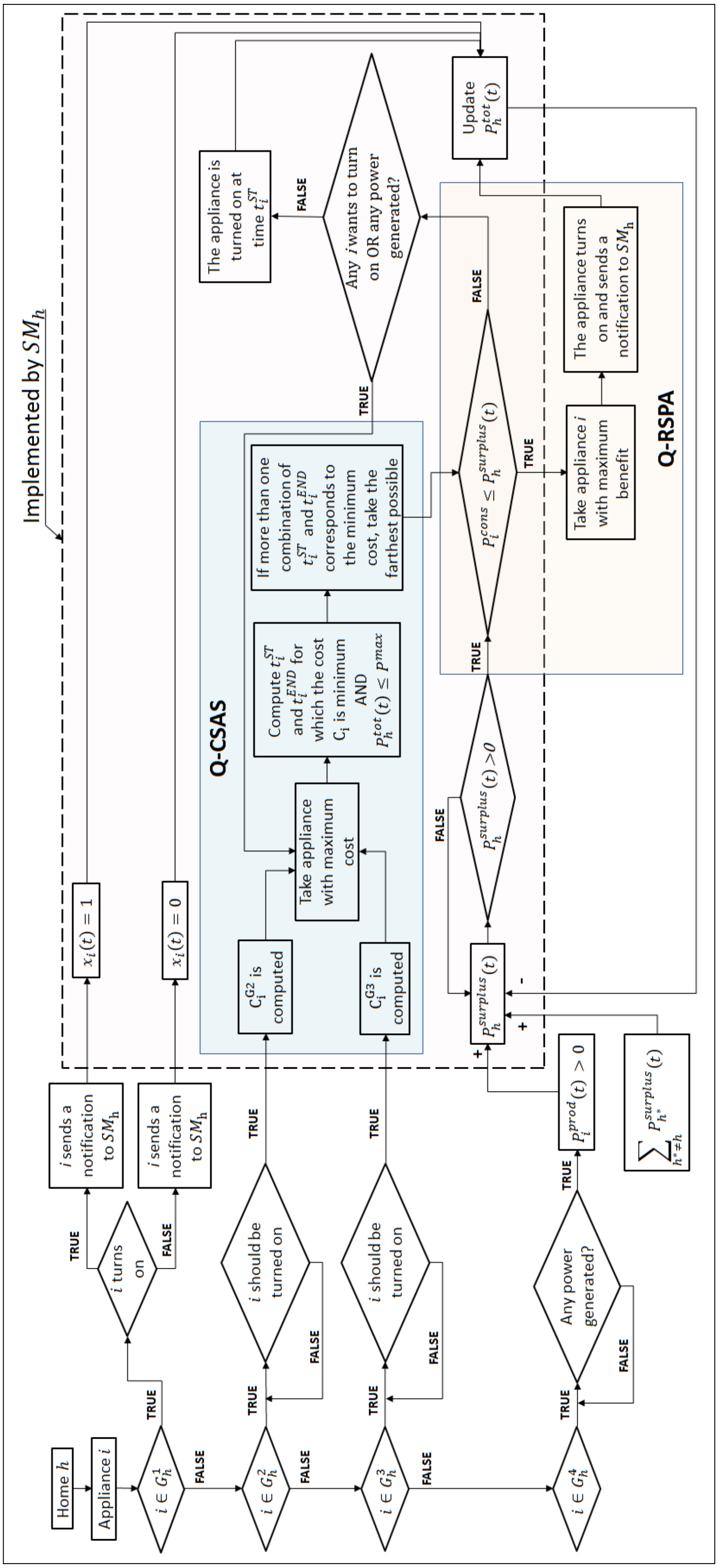

Figure 4.13: Flow chart of the proposed SHEM system.

to the preferred starting time t_i^{PT} for G_h^2 appliances and preferred temperature T_i^{PT} for G_h^3 appliances. The annoyance vector for the profile the user belongs to is also considered. Therefore, the starting time t_i^{ST} is computed by the Q-CSAS according to the user preferences, provided that the available power P^{max} (the maximum power the user can consume on the basis of the contract) is not exceeded by the simultaneous usage of the appliances that made an activation request.

If appliance i is a supply (i.e. it belongs to G_h^4), or a surplus power coming from neighboring houses is detected by the SM_h, SM_h computes the $P_h^{surplus}(t)$ value of the surplus power related to house h at time t. $P_h^{surplus}(t)$ takes into account all the surplus power contributions that are made available by the neighbor houses along with the power supplied by G_h^4 appliances, and it is decreased by the total power $P_h^{tot}(t)$ that is expected to be consumed at time t by the appliances inside home h if they are on $(x_i(t) = 1)$

$$P_h^{surplus}(t) = \sum_{h^* \neq h} P_{h^*}^{surplus}(t) + \sum_{i \in G_h^4} P_i^{prod}(t) - P_h^{tot}(t) \tag{4.24}$$

$$P_h^{tot}(t) = \sum_{i \in G_h^1} P_i^{cons} \cdot Pr_i(t) + \sum_{i \in \left\{G_h^2, G_h^3\right\}} P_i^{cons} \cdot x_i(t) \tag{4.25}$$

Whenever $P_h^{surplus}(t) > 0$ is verified, SM_h broadcasts this information to the appliances it controls.

If there is any G_h^2 or G_h^3 appliance that is waiting to turn on and its power consumption is lower than the available surplus power, Q-RSPA is started. As opposed to Q-CSAS, which schedules the best starting time according to the expected user behavior, Q-RSPA adjusts the starting times that have already been scheduled by the Q-CSAS, in a real time fashion. More precisely, whenever there is a power surplus coming from RES, Q-RSPA evaluates if it is more convenient for appliances which starting time has already been set by Q-CSAS, to turn on immediately rather than waiting for their scheduled t_i^{ST}. If it is, their starting time is changed to the current time. Q-RSPA is a distributed consensus algorithm where appliances compete for the same resource, negotiating among each other. After the algorithm has converged, those appliances that have won the negotiation immediately turn on. If there is any surplus power still available, it is sent to the closest SM.

Cost Saving Appliance Scheduling algorithm

The Q-CSAS is a centralized algorithm based on the concept that tasks should be performed as much as possible during off-peak hours, when electricity cost is lower.

When appliance $i \in \{G_h^2, G_h^3\}$ sends to SM_h an activation request, the SM_h retrieves its preferred starting time t_i^{PT} or its preferred temperature T_i^{PT} and its appliance's usage profile $\hat{\mathbf{Q}}_i$. Consequently, SM_h starts Q-CSAS to assign to all G_h^2 appliances the most convenient starting time, and to all G_h^3 appliances the most convenient starting time and ending times, according to TOU tariffs and QoE annoyance values.

Now, the concept of *relative satisfaction level* is introduced, which is defined as the user perceived quality when an appliance is activated with a difference with respect to preferred time or temperature $\Delta\theta$

$$\sigma(\Delta\theta) = \frac{q^{max} - \hat{q}_i(\Gamma(\Delta\theta))}{q^{max} - q^{min}} \tag{4.26}$$

where q^{max} and q^{min} are the highest and lowest possible values for the annoyance (i.e. respectively 5 and 1), $\hat{q}_i(.)$ is an element of $\hat{\mathbf{Q}}_i$ and $\Gamma(\Delta\theta)$ is a function that outputs the s_y value included in **S** that is closest to $\Delta\theta$. Note that to simplify the notation this function is considered for all types of appliances in G2 and G3.

It is also defined the *cost contribution* of appliance $i \in G_h^2$ starting at time t_i^{ST} and ending at time $t_i^{END} = t_i^{ST} + t_i^{exec}$

$$C_i^{G2}(t_i^{ST}) = \frac{P_i^{cons}}{\sigma\left(\Delta t_i^{ST}\right)} \cdot \int_{t_i^{ST}}^{t_i^{END}} \Phi(t)dt \tag{4.27}$$

where: $\Phi(t)$ is the electricity tariff at time t, and $\sigma\left(\Delta t_i^{ST}\right)$ is the relative satisfaction level for a time interval $\Delta t_i^{ST} = t_i^{ST} - t_i^{PT}$. If $\sigma\left(\Delta t_i^{ST}\right) = 0$, the cost value $C_i^{G2}(t_i^{ST}) \rightarrow \infty$.

For an appliance $i \in G_h^3$, two cases are distinguished: if, at the current time t^{cur}, the inside temperature $T_i^{cur} = T_i^{in}(t^{cur})$ already corresponds to a relative satisfaction level $\sigma\left(\Delta T_i^{cur}\right) = 0$ (e.g. a sudden temperature change can be caused by a user opening a window, or using hot water), the appliance needs to start immediately, and thus its starting time is set to $t_i^{ST} = t^{cur}$, and the system is only left to decide the optimal ending time t_i^{END}. Otherwise, if the inside temperature corresponds to a relative satisfaction level $\sigma\left(\Delta T_i^{cur}\right) > 0$, the system decides both the starting and ending times. Analogously to Eq. (4.27), it is defined the cost contribution of appliance $i \in G_h^3$ starting at time t_i^{ST} and ending at time $t_i^{END} = t_i^{ST} + t_i^{exec}\left(T_i^{exp}\right)$

$$\begin{aligned}
&\textbf{if } \sigma\left(\Delta T_i^{cur}\right) > 0 \\
&\quad C_i^{G3}(t_i^{ST}, t_i^{END}) = \frac{2 \cdot P_i^{cons}}{\sigma\left(\Delta T_i^{ST}\right) + \sigma\left(\Delta T_i^{exp}\right)} \cdot \int_{t_i^{ST}}^{t_i^{END}} \Phi(t)dt \\
&\textbf{else if } \sigma\left(\Delta T^{cur}\right) = 0 \\
&\quad C_i^{G3}(t_i^{cur}, t_i^{END}) = \frac{P_i^{cons}}{\sigma\left(\Delta T_i^{exp}\right)} \cdot \int_{t_i^{cur}}^{t_i^{END}} \Phi(t)dt
\end{aligned} \tag{4.28}$$

again with $\sigma\left(\Delta T_i^{exp}\right) > 0$, where $\sigma\left(\Delta T_i^{ST}\right)$ and $\sigma\left(\Delta T_i^{exp}\right)$ are the relative satisfaction values for a difference in temperature respectively of $\Delta T_i^{ST} = T_i^{in}(t_i^{ST}) - T_i^{PT}$ between the temperature at the starting time and the preferred temperature, and of $\Delta T_i^{exp} = T_i^{exp} - T_i^{PT}$ between the temperature expected at the ending time and the preferred temperature. Recall that $t_i^{exec}\left(T_i^{exp}\right)$ is computed as defined in Eq. (4.18). Also in this case, if $\sigma\left(\Delta T_i^{exp}\right) = 0$, the cost value is $C_i^{G3}(t_i^{ST}, t_i^{END}) \to \infty$.

Let Λ_h be the array of appliances $i \in \{G_h^2, G_h^3\}$ that made an activation request, either because a new task of a G2 appliance has to start, or because the current temperature T_i^{cur} of a G3 appliance corresponds to a relative satisfaction level $\sigma\left(\Delta T^{cur}\right) < 1$.

Given Eqs. (4.27) and (4.28), the problem to be solved by the Q-CSAS algorithm is defined as:

$$\min \sum_{i\in\Lambda_h} \sum_{t,t'=t^{cur}}^{t^{cur}+24\text{h}} C_i^{G2}(t)y_i(t) + C_i^{G3}(t,t')y_i(t)y_i(t') \tag{4.29a}$$

$$s.t. x_i(t) = 1 \;\; \forall t \in \left[t_i^{ST}, t_i^{END}\right], \forall i \in \Lambda_h \tag{4.29b}$$

$$x_i(t) = 0 \;\; \forall t \notin \left[t_i^{ST}, t_i^{END}\right], \forall i \in \Lambda_h \tag{4.29c}$$

$$y_i(t) = 0 \;\; \forall t \neq t_i^{ST}, \qquad y_i(t_i^{ST}) = 1 \tag{4.29d}$$

$$y_i(t') = 0 \;\; \forall t' \neq t_i^{END}, \quad y_i(t_i^{END}) = 1 \tag{4.29e}$$

$$P_h^{tot}(t) \leq P^{max} \quad \forall t, \forall i \in \Lambda_h \tag{4.29f}$$

where the limit to the considered time span has been set to the 24 hours following the current time, constraints (4.29b) and (4.29c) refer to the nodes' status, constraints (4.29d) and (4.29e) guarantee that the cost is only considered if t is the starting time and t' is the ending time for node i, and constraint (4.29f) ensures that the available power P^{max} is not exceeded by the simultaneous usage of considered active appliances.

The optimization only takes into account consumer appliances and their probability to be turned on. It neglects suppliers, whose power is negotiated among appliances during Q-RSPA. Note that it is preferable that appliances wait for available RES power as long as it is possible, so that electrical costs are cut. For this reason, Q-CSAS assigns the farthest possible most convenient t_i^{ST} with same annoyance level.

The problem given by Eq. (4.29) is NP-hard [149], and therefore its complexity scales exponentially with the problem size. To reduce the complexity of the algorithm, and thus its convergence time and energy needed to be run, a greedy approach is proposed, which is characterized by a linear complexity. The concepts on the basis of Q-CSAS are two:

- appliances that consume more energy, i.e., those that present higher values of energy consumption E_i^{cons} (as defined in Section 4.2.1), are those that generate more energy cost saving when they are shifted to off-peak hours, and thus they should be minimized first;

Algorithm 1 Q-CSAS

1: $\widehat{P}^{tot}(t)$ is initialized with the value of $P^{tot}(t)$.
2: **for all** the appliances in Λ_h **do**
3: take appliance i with the highest possible value of function C_i^{G2} or C_i^{G3} (except the case its value is infinite) and find the times t_i^{ST} and t_i^{END} for which this cost value is minimum and the constraints of problem (4.29) are fulfilled
4: **if** more than one combination of t_i^{ST} and t_i^{END} corresponds to the minimum $C_i^{G2}(t_i^{ST})$ or $C_i^{G3}(t_i^{ST}, t_i^{END})$ **then**
5: take the farthest possible
6: **end if**
7: **end for**

- each cost needs to be proportional to the annoyance of anticipating/postponing an appliance starting time, so that the highest costs correspond to the highest values of annoyance, i.e., an appliance is never started when the corresponding annoyance is maximum.

The steps of Q-CSAS are described in Algorithm 1. The appliance with the maximum cost is taken first and then the best solution for it is found. Notice that the condition to take the farthest starting time possible is needed to ensure that, if some $P_h^{surplus}(t)$ becomes available, the appliance has more probability to be able to negotiate its start before the assigned t_i^{ST}. The total power consumption is then updated for the time when the task is expected to be in execution.

Renewable Source Power Allocation algorithm

Whenever SM_h detects some surplus power, whether it is caused by RES belonging to home h or it comes from neighboring SMs, Q-RSPA is started to distribute this power to the appliances that SM_h manages. In particular, since G_h^1 appliances are turned on independently from the SM decisions, Q-RSPA is run to control Λ_h appliances (recall that Λ_h is the array of controlled appliances that made an activation request to the SM).

Since the surplus power value continuously changes, the algorithm needs to be as lightweight as possible to quickly adapt to changes. Furthermore, communication with appliances that are not visible from the SM need to be quick. In the literature there is a large amount of distributed solutions where nodes negotiate to share the available power, mostly based on game theory [150] and consensus [151]. For these reasons, Q-RSPA is chosen to be a distributed algorithm, where appliances negotiate in order to reach a consensus on which one of them should turn on first.

The assumptions on which Q-RSPA is based are analogous to those of Q-CSAS: the pri-

Algorithm 2 Q-RSPA

Let b^{max} be the consensus variable and b_i^{max} be the local consensus variable.
if $i \in G_h^2$ **then** set $b_i^{max} = b_i^{G2}(t^{cur})$.
else if $i \in G_h^3$ **then** set $b_i^{max} = \max_{t_i^{END}} b_i^{G3}(t_i^{END})$
end if
if some $P_h^{surplus}(t) > 0$ is detected by SM_h **then**
    $P_h^{surplus}(t)$ value is broadcast to controlled appliances.
end if
Consensus algorithm is started by SM_h sending the initial benefit value equal to 0.
while there is some surplus power and there are appliances that can use it **do**
    if appliance i receives a message with surplus and benefit values **then**
        if $P_i^{cons} \leq P_i^{surplus}$ and its local benefit value is lower than the received one **then**
            update local consensus value and forward surplus and updated consensus values to neighbours
        else do not update local consensus value and forward surplus and local consensus values to neighbours
        end if
    else consensus is reached. The appliance with the highest benefit, i.e. the one which local consensus value corresponds to the consensus value achieved, turns on.
    end if
end while

ority needs to be given to appliances that present a higher benefit to use the power produced by RES. For appliances belonging to G2, higher benefits correspond to higher energy consumption values (recall that E_i^{cons} is defined by Eq. (4.16)), and higher relative satisfaction levels of starting immediately $\sigma\left(\Delta t_i^{cur}\right)$. The benefit for appliance $i \in G_h^2$ to start at time t^{cur} is defined as

$$b_i^{G2}(t^{cur}) = E_i^{cons} \cdot \sigma\left(\Delta t_i^{cur}\right) \tag{4.30}$$

On the other hand, G3 appliances make an activation request as soon as their inside temperature has reached a value for which the relative satisfaction level has lowered to $\sigma\left(\Delta T^{cur}\right) < 1$, so their benefit of starting immediately will always be equal or higher than that of starting later. Therefore, their benefit to use RES power only depends on their energy consumption value, which in turn depends on the expected temperature value (see Eq. (4.18)). For this reason, the benefit for appliance $i \in G_h^3$ only depends on the ending time and its related relative satisfaction level

$$b_i^{G3}(t_i^{END}) = E_i^{cons}\left(t_i^{END}\right) \cdot \sigma\left(\Delta t_i^{END}\right) \tag{4.31}$$

The problem to be solved by the Q-RSPA algorithm can now be defined as

$$\max \sum_{i\in\Lambda_h} \sum_{t'=t^{cur}}^{t^{cur}+24\text{h}} b_i^{G2}(t^{cur})y_i(t^{cur}) + b_i^{G3}(t')y_i(t^{cur})y_i(t') \tag{4.32a}$$

$$s.t. x_i(t) = 1 \;\; \forall t \in \left[t_i^{ST}, t_i^{END}\right], \forall i \in \Lambda_h \tag{4.32b}$$

$$x_i(t) = 0 \;\; \forall t \notin \left[t_i^{ST}, t_i^{END}\right], \forall i \in \Lambda_h \tag{4.32c}$$

$$\text{if } b_i^{G2}(t^{cur}) = 0 \text{ OR } b_i^{G3}(t') = 0 \Rightarrow y_i(t^{cur}) = 0 \tag{4.32d}$$

$$\text{if } y_i(t^{cur}) = 1 \Rightarrow t_i^{ST} = t^{cur} \;\; \forall i \in G_h^2 \tag{4.32e}$$

$$\text{if } y_i(t') = 1 \Rightarrow t_i^{END} = t' \;\; \forall i \in G_h^3 \tag{4.32f}$$

$$P_h^{surplus}(t) \geq P_i^{cons} \;\; \forall t \in \left[t^{cur}, t_i^{END}\right], \forall i \in \Lambda_h \tag{4.32g}$$

with $P_h^{surplus}$ computed as defined by Eq. (4.24). Again, the limit to the considered time span has been fixed to the 24 hours following the current time. Constraints (4.32b) and (4.32c) again refer to the status of nodes, constraint (4.32d) ensures that, if the benefit is equal to 0, the appliance does not start, and constraints (4.32e) and (4.32f) set the starting and ending time, if appliances are started immediately.

Analogously to the Q-CSAS algorithm, in order to reduce complexity a greedy approach is used to solve this problem. Summarizing, if the available surplus power is sufficient, Q-RSPA assigns it to the appliances characterized by higher benefit values. In order for appliances to reach a consensus on the highest $b_i(t)$ value, a max consensus algorithm is used. Specifically, a Random-Broadcast-Max consensus algorithm has been chosen for its fast convergence to the solution in wireless channels [152].

The steps of Q-RSPA are described in Algorithm 2. In this algorithm, each SM only needs to evaluate its highest benefit possible, i.e., b_i^{G2} for G2 appliances and $\max_{t_i^{END}} b_i^{G3}(t_i^{END})$ for G3 appliances, and to determine some inequalities. Since the complexity of this process is negligible, it can be executed even by the most simple device. Nodes converge to the maximum benefit value in a few steps, therefore almost instantly. As soon as convergence is reached, the node with the highest benefit value sends a notification to the SM_h and immediately turns on. The SM_h updates the new power surplus value according to the power consumption of the node that has just turned on and, if it is still higher than 0, initiates the consensus algorithm again.

4.2.4 Simulation

The proposed SHEM system has been tested in real time supposing to have 1000 houses with user profiles chosen pseudo-randomly according to the probability density function generated by the percentages given in Figures 4.11 and 4.12 about the overall population that fell into a given profile. Power consumption values, mean execution times and probability to have a given appliance at home have been set according to the conducted survey results and to [3,4], and are

Table 4.2: Characteristic parameters of appliances [1,3,4].

Name	**Group**	**Power [Wh]**	**Mean t_i^{exec} [min]**	**Probability to have it**
Fridge/freezer	G1	70	Always on	100%
Lighting	G1	40	Always on when someone is at home	100%
PC/laptop	G1	50	150	95%
TV	G1	30	210	100%
Game console	G1	90	120	5%
Hair dryer	G1	1500	15	100%
Iron	G1	1100	20	100%
Microwave oven	G1	1000	90	52%
Washing machine	G2	600	130	86%
Dishwasher	G2	400	160	34%
Clothes dryer	G2	1300	90	8%
Electric oven	G2	2000	15	53%
HVAC	G3	1000	Always on when someone is at home. Set according to Eq. (4.18)	31%
Water heater	G3	2000	Always on. Set according to Eq. (4.18)	50%
PV system	G4	1250[1]	NA	10%
Wind turbine	G4	500[1]	NA	10%

listed in Table 4.2. The power consumption and execution time values have been set according to a normal distribution with 20% deviation. Also the characteristic parameters that describe the dynamics of G3 appliances have been set with a normal distribution (with 20% deviation) around typical mean values, that are [144]: $P_i^{heat} = 18$ kW, $R_i = 2$ °C/kW and $C_i = 2$ kWh/°C for HVAC; $P_i^{heat} = 5$ kW, $R_i = 120$ °C/kW and $C_i = 0.2$ kWh/°C for WH. Furthermore, two types of RES are included: a photovoltaic (PV) and a microwind turbine system. The produced power has been varied according to a normal distribution (20% deviation) around the values in Figure 4.14, up to a highest value that is consistent with those of commercial home systems [1]. With reference to TOU rates, it has been supposed to use the pricing set by the Italian electricity utility company, ENEL (listed in Table 4.3).

Results in Figure 4.15 show the average electricity cost savings obtained when using the proposed QoE-aware SHEM system, with respect to the case where no SHEM system is used.

[1]This is the maximum produced power. The power produced by RES varies during the day according to a normal distribution around the values in Fig. 4.14

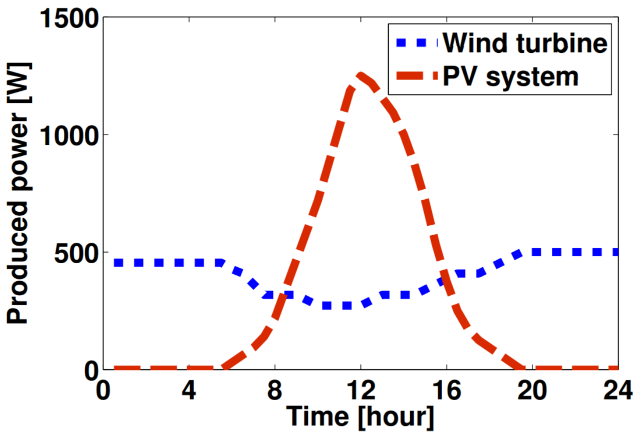

Figure 4.14: Daily power production for photovoltaic (PV) and wind turbine systems [1].

Table 4.3: ENEL pricing.

Weekends, holidays, and everyday from 19:00 to 08:00	Everyday from 8:00 to 19:00
0.12 €/kWh up to 150 kWh/month 0.2 €/kWh over 150 kWh/month	0.53 €/kWh

In order to compare it with a similar one that does not take into account QoE, the QoE-unaware system proposed in [2] is chosen, which only optimizes the starting time with reference to cost saving (QoE-unaware in Figure 4.15). Results are shown both in the case that no RES are installed in the houses (wo RES, i.e. only Q-CSAS is run) and in the case that there are RES installed (w RES). Furthermore, the 95% confidence interval is reported to take into account the variance of results and the number of trials that have been made. For the QoE-aware SHEM system, cost savings amount on average to 22% for the case without RES, and 30% for the case with RES. Note that the highest difference between QoE-aware and QoE-unaware results is experienced for electric oven and HVAC. This behavior is consistent with the results of the survey on the perceived QoE (Section 4.2.2), and it is justified by the fact that these appliances correspond to a higher percentage of people that is less willing to shift their starting time. In the QoE-unaware case, cost saving values are higher, with an average that goes from 33% without RES to 46% with RES.

In order to evaluate the performance of the algorithm with reference to the QoE perceived, the annoyance rate is introduced, computed as the value of the QoE vector element in $\hat{\mathbf{Q}}_i$, for the resulting starting time or temperature. In Figure 4.16, the average annoyance rate evaluated for each controlled appliance and in the absence (wo RES) or presence (w RES) of RES is reported, along with the corresponding 95% confidence interval. Again, the QoE-aware system proposed has been compared with the QoE-unaware system proposed in [2]. With reference to the QoE-aware SHEM system, although cost saving values are considerable, the annoyance rate is still quite close to the lowest one, with an average of 1.65 without RES, and 1.70 with RES. It

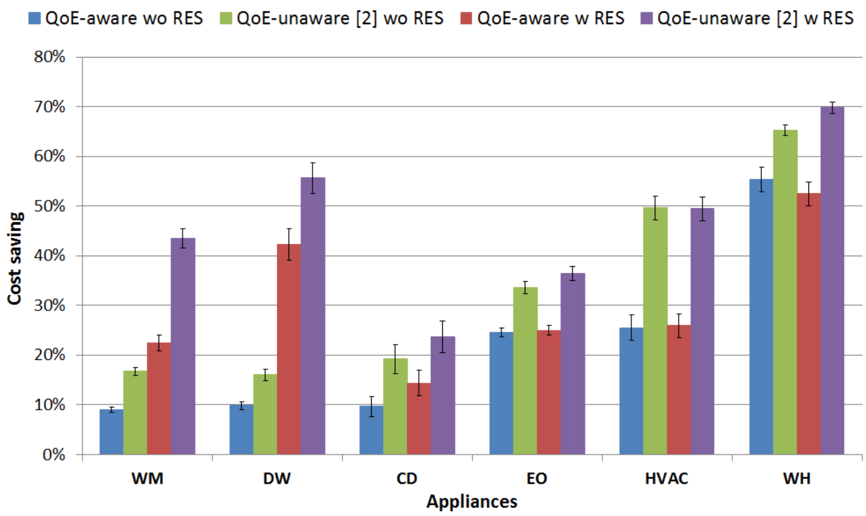

Figure 4.15: Energy cost savings using the proposed QoE-aware SHEM system and the QoE-unaware SHEM system in [2], in the case where RES are not installed (wo RES) and in the case where RES are installed (w RES).

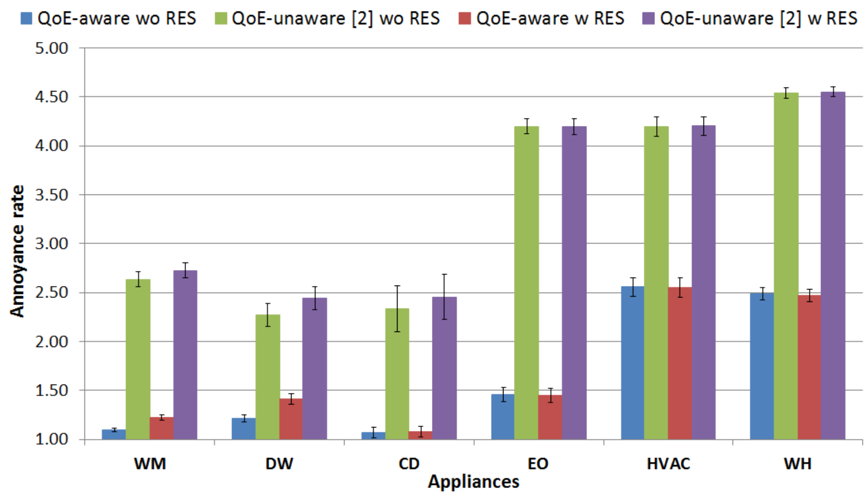

Figure 4.16: Annoyance rate with the proposed QoE-aware SHEM system, compared with the QoE-unaware SHEM system in [2].

is straightforward to note that, even if cost savings are higher using the QoE-unaware algorithm, also the annoyance rate is higher, with an average of 3.36 when there are no RES and 3.43 when RES are installed.

Note that the annoyance rate for the QoE-aware system is sometimes higher when RES are installed in the house. The reason is that, when a RES produces some power, the appliances of the house compete for that power according to the benefit of starting their task immediately, that is in inverse proportion to the relevant level of annoyance of the user (see Eq. (4.32)). Therefore, it may happen that appliances with high power consumption and annoyance level correspond to higher benefit values than appliances with low power consumption but even lower annoyance level. Since RES power is available for a limited amount of time and associated savings are considerable, the SHEM system tries to exploit it all immediately. For this reason, the annoyance level is sometimes higher, particularly for those appliances, such as WM and DW, for which, according to Figures 4.11 and 4.12, users are usually more willing to shift their starting time, in spite of annoyance levels slightly higher. On the other hand, when no RES power is considered, the starting time is only assigned according to electricity tariffs, and thus it is more likely that there is a time, when electricity is cheaper, that is closer to the user preferred time.

4.3 Conclusions

This chapter focused on two different application scenarios in which the QoE is involved as a metric for system optimization and user profiling. The first application scenario investigated the role of the QoE in the collaboration between Internet Service Providers (ISP) and Over The Top (OTT) services. Indeed, as the provision of QoE is considered the common objective for OTTs and ISPs, a QoE-aware collaboration approach between the two entities has been proposed, which is driven by the maximization of the revenue based on different factors, such as the user churn, pricing and marketing actions. The collaboration approach has to aim to overtake the limits of both OTT and ISP that, individually, are not able to guarantee adequate quality service delivery to their customers. In fact, on the one hand, the ISP has the control of the network but it is not able to measure the QoE perceived by the users; on the other hand, the OTT is aware of the QoE perceived by the users but does not have any control on the network. Therefore, the proposed collaboration is guided by the ISP, which maximizes the revenue as a function of the delivered QoE with the provision of better network resources on the basis of the context-aware QoE monitoring provided by the OTT. Simulations are conducted to analyze the potential of the proposed collaboration approach, defined as Joint Venture (JV), with respect to the No Collaboration (NC) approach that does not consider a collaboration between the OTTs and the ISP so that the OTTs deliver their contents through the best effort service over the ISP network. The simulation scenario considered two OTT applications which are delivered to their users through a network owned by an ISP. For both the approaches (NC and JV) and for both the applications (video streaming and VoIP), the users can choose between two different plans: standard plan and premium plan. The price for subscribing to the premium plan is greater than that for subscribing to the standard plan. Simulations results showed that the revenue obtained with the JV approach is always greater than that obtained with the NC approach for both the video and VoIP applications. This is mainly due to the fact that, with the JV approach, the OTTs collaborating with the ISP are able to satisfy the QoE expectations of both the standard and premium users. Specifically, the premium users are those who contribute to the revenue difference between the two approaches. Therefore, if ISPs and OTTs adopt the proposed collaboration approach, they will not only increase the revenue but will also provide better QoE to their users with relatively lower prices.

The second application scenario considered the QoE for a priori user profiling and a posteriori evaluation of the customer comfort in a Smart Home Energy Management (SHEM) system. In the proposed system, the QoE is considered as the degree of annoyance perceived when the starting time or the set temperature of appliances in a Smart Home is modified with respect to users' preferences. A survey has been conducted on a population sample of 427 subjects to collect users' preferences, which have been clustered in different profiles. Based on these results and on the created profiles for each appliance, a Smart Home environment has been created where smart appliances can be easily installed and the proper profile for each user is assigned. It is important to note that the customers adopting the proposed SHEM system do not fill the form used for clustering. Instead, simple annoyance rating questions are made to the customer at the end of those usages which add significant information to user's profiling, so as to learn what the customer preferences are without annoying them with too many interactions. The SHEM system runs a task scheduling model, which relies on two algorithms: the QoE-aware Cost Saving Appliance Scheduling (Q-CSAS) algorithm that is aimed at scheduling controlled loads based on users profile preferences and Time-of-Use (TOU) electricity prices; and the QoE-aware Renewable Source Power Allocation (Q-RSPA) algorithm that modifies the working schedule of appliances whenever a surplus of energy has been made available by renewable sources. The final objective is that of scheduling the appliances operations, such as starting time and set temperature, so that a trade-off between energy expenses and annoyance perceived is achieved. The performance of the proposed QoE-aware SHEM system are compared with respect to the case of a QoE-unaware system (which only optimizes the starting time with reference to cost saving), in terms of energy cost savings and annoyance rate. Results show that the proposed system obtains a significantly lower annoyance perceived by users and similar energy savings, compared to QoE-unaware SHEM systems. Specifically, simulation results carried out using different appliances prove that average energy cost saving using the proposed algorithms goes from 22%, when there are not RES installed in the neighbourhood, to 30% in the presence of RES. The perceived QoE is confirmed not to diverge much from the preferred one, with an average annoyance rate value between 1.65 and 1.70.

Chapter 5

Conclusions and future works

In this thesis, the concept of Quality of Experience (QoE), i.e., *"the degree of delight or annoyance of the user of an application or service"* has been extensively studied with regard to QoE modelling and two different application scenarios in which the QoE is involved as a metric for system optimization and user profiling.

In Chapter 3, QoE modelling is discussed, which aims to define the relationship between different measurable QoE influence factors (IFs) and quantifiable QoE dimensions for a given service scenario. To address the problem of modelling un-interoperability, i.e., the unfeasibility of integrating the results of different modelling activities to broaden the range of scenarios where the integrated model can be applied, a layered modelling approach for evaluating the QoE of multimedia services is proposed. Accordingly, the models are defined in terms of separate layers, each devoted to a specific QoE domain (set of IFs), so that the overall quality can be computed as a combination of all domains. To demonstrate the validity of the proposed layered model, the influence of system and interactivity IFs on the QoE perceived by the users when streaming video sequences on tablet devices are evaluated and combined for the estimation of the overall QoE. The results showed that the interactivity provides an increase of the perceived quality respect to the video without interactivity. Therefore, the influence of the interactivity on the video quality can be considered separately from the influence of system IFs, and it has been successfully translated into both an additive or multiplicative parameter in existing quality models. This means that IFs belonging to different layers can be firstly considered independently and then be combined for estimating the overall QoE. These preliminary results validate the proposed layered model although additional investigation is needed to confirm the obtained results.

Additionally, the influence of device switching on the QoE perceived by users watching video contents was investigated. The aim was to demonstrate that the QoE is not only related to the video consumption on the single device, but it takes into consideration the overall experience of watching the whole video by switching between different devices; for this reason, two devices with very different characteristics and technical capabilities were deliberately chosen, i.e., a TV screen and a tablet. It resulted that low video qualities achieve higher MOS values when the viewing device is a tablet rather than a TV screen; similarly, many users perceived a slight increase in the quality when switching from the TV screen to the tablet, even in the case the quality is kept constant, without a strong effect on the MOS ratings, however. Nevertheless, in this case a QoE model has not been defined because this scenario is too specific. Indeed, the reverse scenario of device switching from a tablet to the TV, and the consideration of additional devices, such as smartphones, are subjects of future works.

Finally, a layered QoE management framework for evaluating the QoE of Multimedia IoT (MIoT) applications is proposed. As a practical use case, a vehicular MIoT application is implemented, which shows in a multimedia way and in real time the state and the position of vehicles during driving lessons together with a video showing a view of the roads traveled by these vehicles. A subjective quality assessment has been conducted to verify the applicability of the proposed approach. It resulted that the QoE predicted by the proposed QoE model is highly correlated with subjective results, which means that it can be used to estimate and control the QoE of the vehicle MIoT application. However, further investigations are needed and additional experiments should be performed with other MIoT applications to verify the model and to introduce further refinements.

In Chapter 4, two different QoE application scenarios are discussed. The first investigated the role of the QoE in the collaboration between Internet Service Providers (ISP) and Over The Top (OTT) services. Indeed, as the provision of QoE is considered the common objective for OTTs and ISPs, a QoE-aware collaboration approach between the two entities has been proposed. The collaboration is guided by the ISP, which maximizes the revenue as a function of the delivered QoE with the provision of better network resources on the basis of the context-aware QoE monitoring provided by the OTT. Simulations are conducted to analyze the potential of the proposed collaboration approach, defined as Joint Venture (JV), with respect to the No Collaboration (NC) approach that does not consider a collaboration between the OTTs and the ISP so that the OTTs deliver their contents through the best effort service over the ISP network. Simulations results showed that the revenue obtained with the JV approach is always greater than that obtained with the NC approach for both the video and VoIP applications. This is mainly due to the fact that, with the JV approach, the OTTs collaborating with the ISP are able to satisfy the QoE expectations of quality demanding users, which are those who contribute more to the revenue difference between the two approaches. Future research should focus on the implementation of QoE-centric interfaces between OTTs and ISPs, the consideration of computational complexity and scalability issues with the increase in the number of OTTs and customers, and the definition of context-aware QoE models.

The second application scenario considered the QoE for a priori user profiling and a posteriori evaluation of the customer comfort in a Smart Home Energy Management (SHEM) system. In the proposed system, the QoE is considered as the degree of annoyance perceived when the starting time or the set temperature of appliances in a Smart Home is modified with respect to users' preferences. A survey has been conducted on a population sample of 427 subjects to collect users' preferences, which have been clustered in different profiles. Based on these results and on the created profiles for each appliance, a Smart Home environment has been created where smart appliances can be easily installed and the proper profile for each user is assigned. The SHEM system runs a task scheduling model, which relies on two algorithms: the QoE-aware Cost Saving Appliance Scheduling (Q-CSAS) algorithm that is aimed at scheduling controlled loads based on users profile preferences and Time-of-Use (TOU) electricity prices; and the QoE-aware Renewable Source Power Allocation (Q-RSPA) algorithm that modifies the working schedule of appliances whenever a surplus of energy has been made available by renewable sources. The final objective is that of scheduling the appliances operations, such as starting time and set temperature, so that a trade-off between energy expenses and annoyance perceived is achieved. The performance of the proposed QoE-aware SHEM system are compared with respect to the case of a QoE-unaware system (which only optimizes the starting time with reference to cost saving), in terms of energy cost savings and annoyance rate. Results show that the proposed system obtains a significantly lower annoyance perceived by users and similar energy savings, compared to QoE-unaware SHEM systems. Specifically, simulation results carried out using different appliances prove that average energy cost saving using the proposed algorithms goes from 22%, when there are not RES installed in the neighbourhood, to 30% in the presence of RES. The perceived QoE is confirmed not to diverge much from the preferred one, with an average annoyance rate value between 1.65 and 1.70. As a future activity, online survey tools may be used to collect users' preferences, such as Qualtrics, SurveyMonkey, SurveyGizmo, which would allow to have better usage clustering results.

Acronyms

ACR	Absolute Category Rating
ALTO	Application-Layer Traffic Optimization
AS	Autonomous System
CDN	Content Delivery Network
CI	Confidence Interval
CIF	Common Intermediate Format
CINA	Collaboration Interface between Network and Application
CIoT	Cognitive Internet of Things
CVO	Composite Virtual Object
DER	Distributed Energy Resources
ELA	Experience Level Agreement
EPZS	Enhanced Predictive Zonal Search
ETSI	European Telecommunications Standards Institute
GGC	Google Global Cache
GOP	Group Of Picture
GPS	Global Positioning System
HAN	Home Area Network
HAS	HTTP Adaptive Streaming
HD	High Definition

HVAC	Heating Ventilation and Air Conditioning
ICT	Information and Communication Technology
IEC	International Electrotechnical Commission
IF	Influence Factor
IoT	Internet of Things
ISO	International Organization for Standardization
ISP	Internet Service Provider
ITU	International Telecommunication Union
IXP	Internet eXchange Points
KPI	Key Performance Indicator
MDV	Multi-Device Viewing
MIoT	Multimedia Internet of Things
MIST	Mobile and Interactive Social TV
MOS	Mean Opinion Score
NGN	Next Generation Networks
OBD	On-Board Diagnostic
OCA	Open Connect Appliance
OTT	Over The Top
P2P	Peer-to-Peer
PLR	Packet Loss Rate
PMP	Paris Metro Pricing
PNI	Private Network Interconnection
PPI	Pixel Per Inch
PPI	Public Peering Interconnection

PVS	Processed Video Sequence
QCIF	Quarter Common Intermediate Format
Q-CSAS	QoE-aware Cost Saving Appliance Scheduling
QoD	Quality of Data
QoE	Quality of Experience
QoI	Quality of Information
QoS	Quality of Service
QoSD	QoS delivered/achieved by service provider
QoSE	QoS experienced/perceived by customer/user
Q-RSPA	QoE-aware Renewable Source Power Allocation
RES	Renewable Energy Source
RFID	Radio-Frequency IDentification
RWO	Real-World Object
SD	Standard Definition
SDP	Smart Data Pricing
SDV	Single Device Viewing
SFI	Settlement Free-Interconnection
SHEM	Smart Home Energy Management
SLA	Service Level Agreement
SM	Smart Meter
SRC	Source Reference Circuit
SVC	Scalable Video Coding
TC	Test Condition
TOU	Time-of-Use

UVLC Universal Variable Length Code

VO Virtual Object

VoD Video on Demand

VoIP Voice over IP

WSN Wireless Sensor Networks

Bibliography

[1] M. Eroglu, E. Dursun, S. Sevencan, J. Song, S. Yazici, and O. Kilic, "A mobile renewable house using PV/wind/fuel cell hybrid power system," *International Journal of Hydrogen Energy*, vol. 36, no. 13, pp. 7985–7992, 2011.

[2] M. Cabras, V. Pilloni, and L. Atzori, "A Novel Smart Home Energy Management System: Cooperative Neighbourhood and Adaptive Renewable Energy Usage," in *Proc. of the IEEE International Conference on Communications (ICC), 2015*. IEEE, 2015, pp. 716–721.

[3] J. Widén, M. Lundh, I. Vassileva, E. Dahlquist, K. Ellegård, and E. Wäckelgård, "Constructing load profiles for household electricity and hot water from time-use data - Modelling approach and validation," *Energy and Buildings*, vol. 41, no. 7, pp. 753–768, 2009.

[4] J. P. Zimmerman, "End-use metering campaign in 400 households in Sweden. Assessment of the potential electricity savings," *Swedish Energy Agency*, 2009.

[5] Cisco, "Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2016–2021," 2016.

[6] "Qualinet White Paper on Definitions of Quality of Experience (2012)," *European Network on Quality of Experience in Multimedia Systems and Services (COST Action IC 1003)*, Patrick Le Callet, Sebastian Möller and Andrew Perkis, eds, Lausanne, Switzerland, Version 1.2, 2013.

[7] S. Baraković and L. Skorin-Kapov, "Survey and challenges of QoE management issues in wireless networks," *Journal of Computer Networks and Communications*, vol. 2013, 2013.

[8] C. Xu, F. Zhao, J. Guan, H. Zhang, and G.-M. Muntean, "QoE-Driven User-Centric VoD Services in Urban Multihomed P2P-Based Vehicular Networks," *IEEE Transactions on Vehicular Technology*, vol. 62, no. 5, pp. 2273–2289, 2013.

[9] C. Xu, S. Jia, M. Wang, L. Zhong, H. Zhang, and G.-M. Muntean, "Performance-Aware Mobile Community-Based VoD Streaming Over Vehicular Ad Hoc Networks," *IEEE Transactions on Vehicular Technology*, vol. 64, no. 3, pp. 1201–1217, 2015.

[10] G. Ghinea and O. Ademoye, "A user perspective of olfaction-enhanced mulsemedia," in *Proc. of the International Conference on Management of Emergent Digital EcoSystems, MEDES '10*. ACM, 2010, pp. 277–280.

[11] Z. Yuan, S. Chen, G. Ghinea, and G.-M. Muntean, "User Quality of Experience of Mulsemedia Applications," *ACM Transactions on Multimedia Computing, Communications, and Applications (TOMM) - Special Issue on Multiple Sensorial (MulSeMedia) Multimodal Media: Advances and Applications*, vol. 11, no. 1, 2014.

[12] Y. Wang, P. Li, L. Jiao, Z. Su, N. Cheng, X. S. Shen, and P. Zhang, "A Data-Driven Architecture for Personalized QoE Management in 5G Wireless Networks," *IEEE Wireless Communications*, vol. 24, no. 1, 2017.

[13] L. G. M. Ballesteros, O. Álvarez, and J. Markendahl, "Quality of Experience (QoE) in the smart cities context: An initial analysis," in *Proc. of the IEEE First International Smart Cities Conference (ISC2), 2015*. IEEE, 2015.

[14] "Definitions of terms related to quality of service," *Recommendation ITU-T E.800*, 2008.

[15] M. Fiedler, T. Hoßfeld, and P. Tran-Gia, "A generic quantitative relationship between Quality of Experience and Quality of Service," *IEEE Network*, vol. 24, no. 2, pp. 36–41, 2010.

[16] P. Reichl, S. Egger, R. Schatz, and A. D'Alconzo, "The Logarithmic Nature of QoE and the Role of the Weber-Fechner Law in QoE Assessment," in *Proc. of the IEEE International Conference on Communications (ICC), 2010*. IEEE, 2010.

[17] A. Takahashi, D. Hands, and V. Barriac, "Standardization activities in the ITU for a QoE assessment of IPTV," *IEEE Communications Magazine*, vol. 46, no. 2, pp. 78–84, 2008.

[18] "New definitions for inclusion in Recommendation ITU-T P.10/G.100," *Recommendation ITU-T P.10/G.100 (2006) - Amendment 2*, 2008.

[19] "Human Factors (HF); Quality of Experience (QoE) requirements for real-time communication services," *ETSI TR 102 643 V1.0.2*, 2010.

[20] "Qualinet official website," http://www.qualinet.eu/.

[21] K. U. R. Laghari and K. Connelly, "Toward total quality of experience: A QoE model in a communication ecosystem," *IEEE Communications Magazine*, vol. 50, no. 4, pp. 58–65, 2012.

[22] K. Kilkki, "Quality of Experience in Communications Ecosystem," *Journal of Universal Computer Science*, vol. 14, no. 5, pp. 615–624, 2008.

[23] K. U. R. Laghari, N. Crespi, B. Molina, and C. E. Palau, "QoE Aware Service Delivery in Distributed Environment," in *Proc. of the IEEE Workshops of International Conference on Advanced Information Networking and Applications (WAINA), 2011*. IEEE, 2011, pp. 837–842.

[24] D. Geerts, K. De Moor, I. Ketykó, A. Jacobs, J. Van den Bergh, W. Joseph, L. Martens, and L. De Marez, "Linking an integrated framework with appropriate methods for measuring QoE," in *Proc. of the Second International Workshop on Quality of Multimedia Experience (QoMEX), 2010*. IEEE, 2010, pp. 158–163.

[25] A. Perkis, "A QoE cross layer approach to model media experiences," *IEEE COMSOC MMTC E-Letter*, vol. 8, no. 2, pp. 6–9, 2013.

[26] L. Skorin-Kapov and M. Varela, "A multi-dimensional view of QoE: the ARCU model," in *Proc. of the 35th International Convention MIPRO, 2012*. IEEE, 2012, pp. 662–666.

[27] S. Baraković, J. Baraković, and H. Bajrić, "QoE Dimensions and QoE Measurement of NGN Services," in *Proc. of the 18th Telecommunications forum TELFOR 2010*, 2010, pp. 15–18.

[28] A. Perkis, S. Munkeby, and O. I. Hillestad, "A model for measuring Quality of Experience," in *Proc. of the 7th Nordic Signal Processing Symposium, 2006. NORSIG 2006*. IEEE, 2006, pp. 198–201.

[29] S. Möller, K.-P. Engelbrecht, C. Kuhnel, I. Wechsung, and B. Weiss, "A taxonomy of quality of service and Quality of Experience of multimodal human-machine interaction," in *Proc. of the International Workshop on Quality of Multimedia Experience, 2009. QoMEx 2009*. IEEE, 2009, pp. 7–12.

[30] M. Volk, J. Sterle, U. Sedlar, and A. Kos, "An approach to modeling and control of QoE in next generation networks," *IEEE Communications Magazine*, vol. 48, no. 8, pp. 126–135, 2010.

[31] S. Jumisko-Pyykkö, “User-Centered Quality of Experience and Its Evaluation Methods for Mobile Television,” *PhD Thesis, Tampere University of Technology*, 2011.

[32] “Methods for subjective determinations of transmission quality,” *Recommendation ITU-T P.800*, 1996.

[33] “Methodology for the subjective assessment of the quality of television pictures,” *Recommendation ITU-R BT.500-13*, 2012.

[34] “Subjective video quality assessment methods for multimedia applications,” *Recommendation ITU-T P.910*, 2008.

[35] T. Zhao, Q. Liu, and C. W. Chen, “QoE in Video Transmission: A User Experience-Driven Strategy,” *IEEE Communications Surveys & Tutorials*, vol. 19, no. 1, pp. 285–302, 2016.

[36] F. De Simone, M. Naccari, M. Tagliasacchi, F. Dufaux, S. Tubaro, and T. Ebrahimi, “Subjective assessment of H.264/AVC video sequences transmitted over a noisy channel,” in *Proc. of the International Workshop on Quality of Multimedia Experience, 2009. QoMEx 2009.* IEEE, 2009, pp. 204–209.

[37] G. Zhai, J. Cai, W. Lin, X. Yang, W. Zhang, and M. Etoh, “Cross-Dimensional Perceptual Quality Assessment for Low Bit-Rate Videos,” *IEEE Transactions on Multimedia*, vol. 10, no. 7, pp. 1316–1324, 2008.

[38] K. Yamagishi and T. Hayashi, “Parametric Packet-Layer Model for Monitoring Video Quality of IPTV Services,” in *Proc. of the IEEE International Conference on Communications, 2008. ICC ’08.* IEEE, 2008, pp. 110–114.

[39] J. Joskowicz and J. Carlo Lopez Ardao, “Enhancements to the opinion model for video-telephony applications,” in *Proc. of the 5th International Latin American Networking Conference. LANC ’09.* ACM, 2009, pp. 87–94.

[40] A. Khan, L. Sun, and E. Ifeachor, “Content-Based Video Quality Prediction for MPEG4 Video Streaming over Wireless Networks,” *Journal of Multimedia*, vol. 4, no. 4, pp. 228–239, 2009.

[41] J. Nightingale, Q. Wang, C. Grecos, and S. Goma, “The Impact of Network Impairment on Quality of Experience (QoE) in H.265/HEVC Video Streaming,” *IEEE Transactions on Consumer Electronics*, vol. 60, no. 2, pp. 242–250, 2014.

[42] Z. Duanmu, K. Zeng, K. Ma, A. Rehman, and Z. Wang, “A Quality-of-Experience Index for Streaming Video,” *IEEE Journal of Selected Topics in Signal Processing*, vol. 11, no. 1, pp. 154–166, 2017.

[43] R. K. P. Mok, E. W. W. Chan, and R. K. C. Chang, “Measuring the Quality of Experience of HTTP video streaming,” in *Proc. of the IFIP/IEEE International Symposium on Integrated Network Management (IM), 2011.* IEEE, 2011, pp. 485–492.

[44] T. Hoßfeld, M. Seufert, M. Hirth, T. Zinner, P. Tran-Gia, and R. Schatz, “Quantification of YouTube QoE via Crowdsourcing,” in *Proc. of the IEEE International Symposium on Multimedia (ISM), 2011.* IEEE, 2011, pp. 494–499.

[45] T. Hoßfeld, R. Schatz, and U. Krieger, “QoE of YouTube Video Streaming for Current Internet Transport Protocols,” in *Measurement, Modelling, and Evaluation of Computing Systems and Dependability and Fault Tolerance*, F. K. and U. Krieger, Eds. Springer, 2014, vol. 8376, pp. 136–150.

[46] S. Mate and I. D. D. Curcio, “Consumer experience study of mobile and Interactive Social Television,” in *Proc. of the IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks & Workshops, 2009. WoWMoM 2009.* IEEE, 2009.

[47] M. Azimi, P. Nasiopoulos, and R. Ward, “Data transmission schemes for DVD-like interactive TV,” *IEEE Transactions on Multimedia*, vol. 8, no. 4, pp. 856–865, 2006.

[48] W.-P. Ken Yiu, X. Jin, and S.-H. Gary Chan, “Distributed Storage to Support User Interactivity in Peer-to-Peer Video Streaming,” in *Proc. of the IEEE International Conference on Communications, 2006. ICC ’06.* IEEE, 2006, pp. 55–60.

[49] J. P. López, M. Slanina, L. Arnaiz, and J. M. Menéndez, “Subjective quality assessment in scalable video for measuring impact over device adaptation,” in *Proc. of the IEEE EUROCON, 2013*. IEEE, 2013, pp. 162–169.

[50] A. Khan, L. Sun, J.-O. Fajardo, I. Taboada, F. Liberal, and E. Ifeachor, “Impact of end devices on subjective video quality assessment for QCIF video sequences,” in *Proc. of the Third International Workshop on Quality of Multimedia Experience (QoMEX), 2011.* IEEE, 2011, pp. 177–182.

[51] N. O. Sidaty, M.-C. Larabi, and A. Saadane, “Influence of video resolution, viewing device and audio quality on perceived multimedia quality for steaming applications,” in *Proc. of the 5th European Workshop on Visual Information Processing (EUVIP), 2014.* IEEE, 2014, pp. 1–6.

[52] D. Vucic and L. Skorin-Kepov, “The impact of mobile device factors on QoE for multi-party video conferencing via WebRTC,” in *Proc. of the 13th International Conference on Telecommunications (ConTEL), 2015.* IEEE, 2015, pp. 1–8.

[53] L. Atzori, A. Iera, and G. Morabito, “The internet of things: A survey,” *Computer Networks*, vol. 54, no. 15, pp. 2787–2805, 2010.

[54] J. Gubbi, R. Buyya, S. Marusic, and M. Palaniswami, “Internet of things (iot): A vision, architectural elements, and future directions,” *Future Generation Computer Systems*, vol. 29, no. 7, pp. 1645–1660, 2013.

[55] D. Miorandi, S. Sicari, F. De Pellegrini, and I. Chlamtac, “Internet of things: Vision, applications and research challenges,” *Ad Hoc Networks*, vol. 10, no. 7, pp. 1497–1516, 2012.

[56] A. Al-Fuqaha, M. Guizani, M. Mohammadi, M. Aledhari, and M. Ayyash, “Internet of Things: A Survey on Enabling Technologies, Protocols, and Applications,” *IEEE Communication Surveys & Tutorials*, vol. 17, no. 4, pp. 2347–2376, 2015.

[57] Z. Yang, Y. Yue, Y. Yang, Y. Peng, X. Wang, and W. Liu, “Study and application on the architecture and key technologies for IOT,” in *Proc. of the International Conference on Multimedia Technology (ICMT), 2011.* IEEE, 2011, pp. 747–751.

[58] L. Li, S. Li, and S. Zhao, “QoS-Aware Scheduling of Services-Oriented Internet of Things,” *IEEE Transactions on Industrial Informatics*, vol. 10, no. 2, pp. 1497–1505, 2014.

[59] R. Duan, X. Chen, and T. Xing, “A QoS Architecture for IOT,” in *Proc. of the 2011 International Conference on Internet of Things and 4th International Conference on Cyber, Physical and Social Computing. ITHINGSCPSCOM ’11.* IEEE, 2011, pp. 717–720.

[60] H. Suo, J. Wan, C. Zou, and J. Liu, “Security in the Internet of Things: A Review,” in *Proc. of the International Conference on Computer Science and Electronics Engineering 2012*. IEEE, 2012, pp. 648–651.

[61] M. Wu, T.-J. Lu, F.-Y. Ling, J. Sun, and H.-Y. Du, "Research on the architecture of Internet of Things," in *Proc. of the 3rd International Conference on Advanced Computer Theory and Engineering (ICACTE), 2010*. IEEE, 2010, pp. 484–487.

[62] R. Khan, S. U. Khan, R. Zaheer, and S. Khan, "Future Internet: The Internet of Things Architecture, Possible Applications and Key Challenges," in *Proc. of the 10th International Conference on Frontiers of Information Technology (FIT), 2012*. IEEE, 2012, pp. 257–260.

[63] W. Chen, "An IBE-based security scheme on Internet of Things," in *Proc. of the IEEE 2nd International Conference on Cloud Computing and Intelligent Systems (CCIS), 2012*. IEEE, 2012, pp. 1046–1049.

[64] "EU FP7 Internet of Things Architecture Project."

[65] "iCore project official website," http://www.iot-icore.eu/.

[66] R. Girau, S. Martis, and L. Atzori, "Lysis: A Platform for IoT Distributed Applications Over Socially Connected Objects," *IEEE Internet of Things Journal*, vol. 40, no. 1, pp. 40–51, 2017.

[67] J. Aráuz and T. Fynn-Cudjoe, "Actuator Quality in the Internet of Things," in *Proc. of the 10th Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks (SECON), 2013*. IEEE, 2013, pp. 34–42.

[68] Q. Wu, G. Ding, Y. Xu, S. Feng, Z. Du, J. Wang, and K. Long, "Cognitive Internet of Things: A New Paradigm Beyond Connection," *IEEE Internet of Things Journal*, vol. 1, no. 2, pp. 129–143, 2014.

[69] Y. Ikeda, S. Kouno, A. Shiozu, and K. Noritake, "A framework of scalable QoE modeling for application explosion in the Internet of Things," in *Proc. of the IEEE 3rd World Forum on Internet of Things (WF-IoT), 2016*. IEEE, 2016, pp. 425–429.

[70] "Speech and multimedia Transmission Quality (STQ); Quality of Experience; A Monitoring Architecture," *ETSI TS 103 294 V1.1.1*, 2014.

[71] T. Minhas and M. Fiedler, "Quality of Experience Hourglass Model," in *Proc. of of the IEEE International Conference on Computing, Management and Telecommunications (ComManTel), 2013*. IEEE, 2013, pp. 87–92.

[72] J. Seppänen, M. Varela, and A. Sgora, "An autonomous QoE-driven network management framework," *Journal of Visual Communication and Image Representation*, vol. 25, no. 3, pp. 565–577, 2014.

[73] T. Hoßfeld, R. Schatz, M. Varela, and C. Timmerer, "Challenges of qoe management for cloud applications," *IEEE Communications Magazine*, vol. 50, no. 4, pp. 28–36, 2012.

[74] F. Delli Priscoli, C. Gori Giorgi, S. Monaco, and V. Suraci, "Future Internet Architecture: Control-based Perspectives related to Quality of Experience (QoE) Management," in *Proc. of the 34th Chinese Control Conference (CCC), 2015*. IEEE, 2015, pp. 6475–6482.

[75] "MPEG-V," http://mpeg.chiariglione.org/standards/mpeg-v.

[76] C. Timmerer, J. Gelissen, M. Waltl, and H. Hellwagner, "Interfacing with virtual worlds," http://mpeg.chiariglione.org/sites/default/files/files/standards/docs/MPEG-V.pdf.

[77] S.-K. Kim and M. Preda, "MPEG-V International Standard and the Internet of Things," in *Proc. of the International Conference on Software Intelligence Technologies and Applications and International Conference on Frontiers of Internet of Things 2014*. IEEE, 2014, pp. 166–173.

[78] "MPEG Exploration Part 16, Internet of Media Things and Wearables," http://mpeg.chiariglione.org/standards/exploration/media-centric-internet-things.

[79] Y. Song, B. Ciubotaru, and G.-M. Muntean, "A Cross-Layer Quality-Oriented Scheme for Energy-Efficient Multimedia Delivery in Wireless Networks," *IEEE Transactions on Vehicular Technology*, vol. 65, no. 10, pp. 8554–8566, 2016.

[80] J. Mitola, J. Guerci, J. Reed, Y.-D. Yao, Y. Chen, T. C. Clancy, J. Dwyer, H. Li, H. Man, R. McGwier, and Y. Guo, "Accelerating 5G QoE via public-private spectrum sharing," *IEEE Communications Magazine*, vol. 52, no. 5, pp. 77–85, 2014.

[81] C. Tselios and G. Tsoli, "On QoE-awareness through virtualized probes in 5G networks," in *Proc. of the IEEE 21st International Workshop on Computer Aided Modelling and Design of Communication Links and Networks (CAMAD), 2016*. IEEE, 2016, pp. 159–164.

[82] M. S. Mushtaq, S. Fowler, B. Augustin, and A. Mellouk, "QoE in 5G cloud networks using multimedia services," in *Proc. of the IEEE Wireless Communications and Networking Conference (WCNC), 2016*. IEEE, 2016.

[83] J. Zeng, L. T. Yang, H. Ning, and J. Ma, "A Systematic Methodology for Augmenting Quality of Experience in Smart Space Design," *IEEE Wireless Communications*, vol. 22, no. 4, pp. 81–87, 2015.

[84] B.-H. Chu, M.-S. Tsai, and C.-S. Ho, "Toward a hybrid data mining model for customer retention," *Knowledge-Based Systems*, vol. 20, no. 8, pp. 703–718, 2007.

[85] "Nokia White Paper, Quality of Experience (QoE) of mobile services: Can it be measured and improved?" http://afutt.org/Qostic/qostic1/MOB-GD-MGQ-NOKIA-040129-Nokia-whitepaper_qoe_net-final.pdf.

[86] "Customer Service, Not Price, Remains Top Cause of Customer Churn, Accenture Study Finds," https://newsroom.accenture.com/subjects/customer-relationship-management/customer-service-not-price-remains-top-cause-customer-churn-accenture-study-finds.htm.

[87] T. Hoßfeld, M. Fiedler, and T. Zinner, "The QoE provisioning-delivery-hysteresis and its importance for service provisioning in the Future Internet," in *Proc. of the 7th EURO-NGI Conference on Next Generation Internet (NGI)*. IEEE, 2011, pp. 1–8.

[88] S. Ellouze, B. Mathieu, T. Ahmed, and N. Schwan, "Collaboration between Networks and Applications in the Future Internet," in *Media Networks - Architectures, Applications, and Standards*, H. Moustafa and S. Zeadally, Eds. CRC Press, 2012, pp. 121–140.

[89] "Application-Layer Traffic Optimization (ALTO) Protocol," https://tools.ietf.org/html/rfc7285, 2015, iETF RFC 7285.

[90] "ENVISION FP7 Project official website," http://www.envision-project.org/, 2012.

[91] "Google Edge Network," https://peering.google.com/.

[92] "Microsoft peering," https://www.microsoft.com/Peering.

[93] "Netflix Open Connect," https://openconnect.netflix.com.

[94] N. Lior, "Sustainable energy development: The present (2009) situation and possible paths to the future," *Energy*, vol. 35, no. 10, pp. 3976–3994, 2010.

[95] M. Pipattanasomporn, M. Kuzlu, and S. Rahman, "An Algorithm for Intelligent Home Energy Management and Demand Response Analysis," *IEEE Transactions on Smart Grid*, vol. 3, no. 4, pp. 2166–2173, 2012.

[96] M. Kuzlu, M. Pipattanasomporn, and S. Rahman, “Hardware Demonstration of a Home Energy Management System for Demand Response Applications,” *IEEE Transactions on Smart Grid*, vol. 3, no. 4, pp. 1704–1711, 2012.

[97] M. Erol-Kantarci and H. T. Mouftah, “Wireless Sensor Networks for Cost-Efficient Residential Energy Management in the Smart Grid,” *IEEE Transactions on Smart Grid*, vol. 2, no. 2, pp. 314–325, 2011.

[98] K. M. Tsui and S. C. Chan, “Demand Response Optimization for Smart Home Scheduling Under Real-Time Pricing,” *IEEE Transactions on Smart Grid*, vol. 3, no. 4, pp. 1812–1821, 2012.

[99] O. Elma and U. S. Selamogullari, “A New Home Energy Management Algorithm with Voltage Control in a Smart Home Environment,” *Energy*, vol. 91, pp. 720–731, 2015.

[100] M. Pedrasa, T. Spooner, and I. MacGill, “Coordinated Scheduling of Residential Distributed Energy Resources to Optimize Smart Home Energy Services,” *IEEE Transactions on Smart Grid*, vol. 1, no. 2, pp. 134–143, 2010.

[101] P. Du and N. Lu, “Appliance Commitment for Household Load Scheduling,” *IEEE Transactions on Smart Grid*, vol. 2, no. 2, pp. 411–419, 2011.

[102] H.-C. Jo, S. Kim, and S.-K. Joo, “Smart Heating and Air Conditioning Scheduling Method Incorporating Customer Convenience for Home Energy Management System,” *IEEE Transactions on Consumer Electronics*, vol. 59, no. 2, pp. 316–322, 2013.

[103] M. Bozchalui, S. Hashmi, H. Hassen, C. Canizares, and K. Bhattacharya, “Optimal Operation of Residential Energy Hubs in Smart Grids,” *IEEE Transactions on Smart Grid*, vol. 3, no. 4, pp. 1755–1766, 2012.

[104] B. Asare-Bediako, W. Kling, and P. Ribeiro, “Multi-agent System Architecture for Smart Home Energy Management and Optimization,” in *Proc. of the 4th IEEE/PES Innovative Smart Grid Technologies Europe (ISGT EUROPE), 2013*, 2013, pp. 1–5.

[105] Y. Ozturk, D. Senthilkumar, S. Kumar, and G. Lee, “An Intelligent Home Energy Management System to Improve Demand Response,” *IEEE Transactions on Smart Grid*, vol. 4, no. 2, pp. 694–701, 2013.

[106] T.-H. Chang, M. Alizadeh, and A. Scaglione, “Real-Time Power Balancing Via Decentralized Coordinated Home Energy Scheduling,” *IEEE Transactions on Smart Grid*, vol. 4, no. 3, pp. 1490–1504, 2013.

[107] L. Zhou, Z. Yang, Y. Wen, H. Wang, and M. Guizani, “Resource Allocation with Incomplete Information for QoE-Driven Multimedia Communications,” *IEEE Transactions on Wireless Communications*, vol. 12, no. 8, pp. 3733–3745, 2013.

[108] V. De Silva, X. Shi, B. Evans, J. P. Trufero, and G. Peters, “Designing a QoE Aware Intelligent Home Gateway for Future Smart Homes,” in *Proc. of the Future Network and Mobile Summit (FutureNetworkSummit), 2013*. IEEE, 2013.

[109] K. J. Patel, S. V. Anand, and S. S. Kumart, “A robust QoS framework on Android for effective media delivery to DLNA Enabled Home gateway in smart home environment,” in *Proc. of the IEEE International Conference on Wireless Communications, Networking and Information Security (WCNIS), 2010*. IEEE, 2010, pp. 217–222.

[110] S. Veleva, D. Davcev, and V. Glamocanin, “Dynamic QoS and QoE balancing model for smart Home Energy Management Systems,” in *Proc. of the IEEE International Workshop on Applied Measurements for Power Systems (AMPS), 2012*. IEEE, 2012.

[111] L. Zhou, J. Rodrigues, and L. Oliveira, “QoE-driven power scheduling in smart grid: architecture, strategy, and methodology,” *IEEE Communications Magazine*, vol. 50, no. 5, pp. 136–141, 2012.

[112] “YUV video sequences,” http://trace.eas.asu.edu/yuv/.

[113] “H.264/AVC reference software,” http://iphome.hhi.de/suehring/tml/.

[114] “Matteo Naccari software,” https://sites.google.com/site/matteonaccari/software.

[115] “POLIMI: Database of H.264/AVC video sequences transmitted over a noisy channel,” http://vqa.como.polimi.it/sequences.htm.

[116] S. Wenger, “Proposed Error Patterns for Internet Experiments,” http://ftp3.itu.ch/av-arch/video-site/9910_Red/q15i16.zip, 1999.

[117] “FFMPEG documentation,” http://www.ffmpeg.org/documentation.html.

[118] J. Lang, “Expression Encoder. Best Practices for live smooth streaming broadcasting. Microsoft Corporation,” http://www.streamingmedia.com/conferences/west2010/presentations/smwest-2010-expression-encoder.pdf.

[119] D. C. Robinson, Y. Jytras, and V. Craciun, “Subjective video quality assessment of HTTP adaptive streaming technologies,” *Bell Labs Technical Journal*, vol. 16, no. 4, pp. 5–23, 2012.

[120] “Node.js official page,” https://nodejs.org.

[121] “WebSocket protocol official page,” http://www.websocket.org.

[122] “Socket.IO official page,” http://socket.io/.

[123] “Snellen chart,” http://www.provisu.ch/Age/Snellenchart_en.pdf.

[124] “Arduino mega 2560,” http://arduino.cc/en/Main/ArduinoBoardMega2560.

[125] “Telit official website,” http://www.telit.com/.

[126] S. Sen, C. Joe-Wong, S. Ha, and M. Chiang, “Smart Data Pricing (SDP): Economic solutions to network congestion,” in *Recent Advances in Networking*, H. Haddadi and O. Bonaventure, Eds., 2013, pp. 221–274.

[127] A. Odlyzko, “Paris Metro Pricing for the Internet,” in *Proc. of the 1st ACM conf. on Electronic commerce*. ACM, 1999, pp. 140–147.

[128] S. Wahlmueller, P. Zwickl, and P. Reichl, “Pricing and regulating Quality of Experience,” in *Proc. of the 8th EURO-NGI Conference on Next Generation Internet (NGI), 2012*. IEEE, 2012, pp. 57–64.

[129] M. Varela, P. Zwickl, P. Reichl, M. Xie, and H. Schulzrinne, “From Service Level Agreements (SLA) to Experience Level Agreements (ELA): The challenges of selling QoE to the user,” in *Proc. of the IEEE International Conference on Communication Workshop (ICCW) 2015*. IEEE, 2015, pp. 1741–1746.

[130] M. Leppaniemi and H. Karjaluoto, “Factors Influencing Consumers’ Willingness to Accept Mobile Advertising: a Conceptual Model,” *International Journal of Mobile Communications*, vol. 3, no. 3, pp. 197–213, 2005.

[131] P. Srinuan, C. Srinuan, and E. Bohlin, “An Empirical Analysis of Multiple Services and Choices of Consumer in the swedish Telecommunications Market,” *Telecommunications Policy*, vol. 38, no. 5, pp. 449–459, 2014.

[132] I. Abdeljaouad and A. Karmouch, “Monitoring IPTV Quality of Experience in overlay networks using utility functions,” *Journal of Network and Computer Applications*, vol. 54, pp. 1–10, 2015.

[133] N. J. Nilsson, *Artificial intelligence: a new synthesis*. Morgan Kaufmann, 1998.

[134] B. Karlik and A. V. Olgac, “Performance Analysis of Various Activation Functions in Generalized MLP Architectures of Neural Networks,” *International Journal of Artificial Intelligence and Expert Systems*, vol. 1, no. 4, pp. 111–122, 2011.

[135] G. Gómez, J. Lorca, R. García, and Q. Pérez, “Towards a QoE-driven resource control in LTE and LTE-A networks,” *Journal of Computer Networks and Communications*, vol. 2013, 2013.

[136] P. Oliver-Balsalobre, M. Toril, S. Luna-Ramírez, and J. M. R. Avilés, “Self-tuning of scheduling parameters for balancing the Quality of Experience among services in LTE,” *EURASIP Journal on Wireless Communications and Networking*, vol. 2016, no. 1, pp. 1–12, 2016.

[137] “The E-model: a computational model for use in transmission planning.” Recommendation ITU-T G.107, 2015.

[138] R. G. Cole and J. H. Rosenbluth, “Voice over IP performance monitoring,” *ACM SIGCOMM Computer Communication Review*, vol. 31, no. 2, pp. 9–24, 2001.

[139] Cisco, “Voice Over IP - Per Call Bandwidth Consumption,” https://www.cisco.com/c/en/us/support/docs/voice/voice-quality/7934-bwidth-consume.html.

[140] YouTube, “Live encoder settings, bitrates and resolutions,” https://support.google.com/youtube/answer/2853702?hl=en.

[141] N. Shetty, G. Schwartz, and J. Walrand, “Internet QoS and Regulations,” *IEEE/ACM Transactions on Networking*, vol. 18, no. 6, pp. 1725–1737, 2010.

[142] J. Twidell and T. Weir, *Renewable energy resources*. Routledge, 2015.

[143] N. Lu, “An evaluation of the HVAC load potential for providing load balancing service,” *IEEE Transactions on Smart Grid*, vol. 3, no. 3, pp. 1263–1270, 2012.

[144] J. Mathieu, M. Dyson, D. Callaway, and A. Rosenfeld, “Using residential electric loads for fast demand response: The potential resource and revenues, the costs, and policy recommendations,” *Proc. of the ACEEE Summer Study on Buildings*, 2012.

[145] T. Hoßfeld, C. Keimel, M. Hirth, B. Gardlo, J. Habigt, K. Diepold, and P. Tran-Gia, “Best Practices for QoE Crowdtesting: QoE Assessment With Crowdsourcing,” *IEEE Transactions on Multimedia*, vol. 16, no. 2, pp. 541–558, 2014.

[146] J. B. MacQueen, “Some methods for classification and analysis of multivariate observations,” in *Proc. of the 5th Berkeley Symposium on Mathematical Statistics and Probability*, vol. 1, 1967, pp. 281–297.

[147] D. Arthur and S. Vassilvitskii, “k-means++: The Advantages of Careful Seeding,” in *Proc. of the eighteenth annual ACM-SIAM symposium on Discrete algorithms, SODA ’07*, 2007, pp. 1027–1035.

[148] P. J. Rousseeuw, “Silhouettes: A graphical aid to the interpretation and validation of cluster analysis,” *Journal of Computational and Applied Mathematics*, vol. 20, pp. 53–65, 1987.

[149] V. Pilloni and L. Atzori, “Deployment of Distributed Applications in Wireless Sensor Networks,” *Sensors*, vol. 11, no. 8, pp. 7395–7419, 2011.

[150] L. Militano, A. Iera, A. Molinaro, and F. Scarcello, “Energy-Saving Analysis in Cellular-WLAN Cooperative Scenarios,” *IEEE Transactions on Vehicular Technology*, vol. 63, no. 1, pp. 478–484, 2014.

[151] A. Vaccaro, V. Loia, G. Formato, P. Wall, and V. Terzija, “A Self-Organizing Architecture for Decentralized Smart Microgrids Synchronization, Control, and Monitoring,” *IEEE Transactions on Industrial Informatics*, vol. 11, no. 1, pp. 289–298, 2015.

[152] F. Iutzeler, P. Ciblat, and J. Jakubowicz, “Analysis of Max-Consensus Algorithms in Wireless Channels,” *IEEE Transactions on Signal Processing*, vol. 60, no. 11, pp. 6103–6107, 2012.

List of Publications Related to the Thesis

Published papers

Journal papers

- A. Ahmad, A. Floris, and L. Atzori, *QoE-centric Service Delivery: A Collaborative Approach among OTTs and ISPs.* Computer Networks, Vol. 110, pp. 168–179, Dec. 2016.
- A. Floris, and L. Atzori, *Managing the Quality of Experience in the Multimedia Internet of Things: A Layered-Based Approach.* Sensors, Vol. 16, No. 12, Dec. 2016.
- V. Pilloni, A. Floris, A. Meloni and L. Atzori, *Smart Home Energy Management Including Renewable Sources: A QoE-driven Approach.* IEEE Transactions on Smart Grid, Sept. 2016.
- L. Atzori, A. Floris, G. Ginesu, and D.D. Giusto, *Quality Perception when Streaming Video on Tablet Devices.* Journal of Visual Communication and Image Representation, Vol. 25, No. 3, pp. 586–595, April 2014.

Conference papers

- A. Ahmad, A. Floris, and L. Atzori, "QoE-aware service delivery: A joint-venture approach for content and network providers," in *Proc. of Eighth International Conference on Quality of Multimedia Experience (QoMEX) 2016,* pp. 1–6, Lisbon, Portugal, June 2016.
- A. Floris, A. Meloni, V. Pilloni, and L. Atzori, "A QoE-Aware Approach for Smart Home Energy Management," in *Proc. of IEEE Global Communications Conference (GLOBECOM) 2015,* pp. 1–6, San Diego, CA, Dec. 2015.
- A. Floris, and L. Atzori, "Quality of Experience in the Multimedia Internet of Things: definition and practical use-cases," in *Proc. of IEEE International Conference on Communication Workshop (ICCW) 2015,* pp. 1747–1752, London, UK, June 2015.
- A. Floris, L. Atzori, and G. Ginesu, "The Impact of Interactivity on the QoE: a Preliminary Analysis," in *Proc. of IEEE International Conference on Communication Workshop (ICCW) 2015,* pp. 1711–1716, London, UK, June 2015.
- N. Abis, A. Floris, S. Argyropoulos, L. Atzori, and A. Raake, "I have to switch the terminal: evaluating the impact on video quality perception," in *Proc. of IEEE International Conference on Communications (ICC) 2015*, pp. 6977–6982, London, UK, June 2015.
- A. Floris, L. Atzori, and G. Ginesu, "Addressing un-Interoperability Issues in QoE Models: Is a Layered Modelling Effective?," in *Proc. of IEEE International Conference on Communications Workshops (ICC) 2014,* pp. 563–568, Sidney, Australia, June 2014.