DEGREE PROJECT IN COMPUTER SCIENCE AND COMPUTER ENGINEERING,
SECOND LEVEL
STOCKHOLM, SWEDEN 2017

Evaluation of the Profitability of Quality of Experience-based Resource Allocation Deployment in LTE Network

A Techno-economic Assessment based on Quality of Experience in Video Traffic

URI ARTA RAMADHANI

KTH ROYAL INSTITUTE OF TECHNOLOGY
INFORMATION AND COMMUNICATION TECHNOLOGY

Evaluation of the Profitability of Quality of Experience-based Resource Allocation Deployment in LTE Network

A Techno-economic Assessment based on Quality of Experience in Video Traffic

Uri Arta Ramadhani

2017-11-21

Master's Thesis

Examiner
Gerald Q. Maguire Jr.

Academic adviser
Mohammad Istiak Hossain and Luis Guillermo Martinez Ballesteros

KTH Royal Institute of Technology
School of Information and Communication Technology (ICT)
Department of Communication Systems
SE-100 44 Stockholm, Sweden

Abstract

In the current mobile telecommunication market, with slow growth in mobile subscriptions and increasing traffic demand, each mobile operator needs to manage their customer loyalty in order to maintain position in the market. To retain their customer's loyalty, the user quality of satisfaction needs to be preserved. Integrating a Quality of Experience (QoE) approach into a radio resource scheduling scheme can be a means to improve user quality of satisfaction to a service. However, the enhancement of existing resource allocation management to support a QoE-based resource scheduling scheme needs a careful consideration since it will impact the mobile operator's investment cost. A profitability assessment of QoE-based resource allocation is required as a basis for the mobile operator to forecast their potential benefit of QoE-based resource scheduling deployment.

This thesis investigated the profitability of deploying QoE-based radio resource management (RRM) in terms of revenue loss compared to proportional fair (PF) scheduling, a widely used resource allocation scheme, in delivering a streaming video service. In QoE-based RRM, a buffering percentage experienced by a user was considered in the resource allocation decision process. The two scheduling schemes were simulated in different network configurations. User satisfaction was quantified in terms of mean opinion score. Given the degree of satisfaction for each user, a number of users who would be likely to churn was obtained. A cost-benefit assessment was then conducted by predicting revenue loss due to customer churn.

The results from the simulation and cost analysis show that although QoE-based resource scheduling provides users with a higher degree of satisfaction for more base stations, the utilization of a QoE-based resource scheduler does not offer significant benefit to the network operator with regard to revenue loss and deployment cost when compared to a PF scheduler. This outcome indicates that if the business target is to reduce customer churn, then the operator should utilize a PF scheduler for their RRM scheme.

Keywords: Quality of Experience, radio resource management, video quality, mean opinion score, revenue loss

Sammanfattning

Den nuvarande mobiltelefonimarknaden kännetecknas av svag tillväxt av nya kunder men ett ökat nyttjande bland existerande kunder av företagens tjänster. Kundlojalitet har blivit en avgörande faktor för att uppnå en stark marknadsposition. Kundernas upplevda kvalitet utav mobiltjänsterna behöver upprätthållas på en hög nivå för att tillfredställa denna lojalitet. Att applicera en upplevad kvalitet (QoE) metod i en radio resurs kan vara ett medel till att förbättra kundernas upplevda kvalitet av mobiltjänsten. För att undersöka ifall en sådan tjänst är lönsam är det dock nödvändigt att en lönsamhetskalkyl genomförs, där investeringskostnad och systemets driftkostnad vägs mot eventuella intäkter. En lönsamhetsbedömning av QoE-baserad resursallokering krävs som grund för mobiloperatören att förutse deras potentiella fördelar med QoE-baserad resursschemaläggning.

Denna uppsats undersöker lönsamheten av att implementera QoE i termer av förlorade intäkter, jämfört med proportionell rättvis (PF) schemaläggning, i att leverera en videoströmservice. I QoE-baserad RRM användes buffertprocentandel som användes av användarna i resursallokeringsprocessen. De två olika systemen simulerades genom att använda olika antal basstationer i mobilnätverkskonfigurationen. Användarnöjdhet kvantifierades genom att låta användarna betygsätta tjänsten, detta värde användes därefter till att uppskatta hur många av kunderna som sannolikt ej skulle återanvända tjänsten. En lönsamhetskalkyl genomfördes genom att prediktera förlorade intäkter med avseende på kunderna som ej skulle återanvända tjänsten.

Resultaten från simulerings- och lönsamhetsberäkningen visade att även om QoE erbjuder en högre kundnöjdhet av tjänsten och tillfredsställelse för fler basstationer, så leder inte en QoE-implementering till signifikanta fördelar för nätverket i termer av förlorade intäkter och investeringskostnader jämfört med ett PF schemaläggare. Detta indikerar att om ett företags mål är att höja kundlojaliteten, då skall företaget applicera en PF schemaläggare istället för QoE.

Nyckelord: upplevad kvalitet, radio resurshantering, videokvalitét, medelvärde av graderingarna, inkomstförlust

Acknowledgements

I would like to offer my sincere gratitude to my thesis supervisors, Dr. Luis Guillermo Martinez Ballesteros and Mohammad Istiak Hossain, for the opportunity to do this Master's thesis and providing me with continuous supports and dedication throughout the project.

I would also like to thank Prof. Gerald Q. Maguire Jr., as the examiner of this thesis, for the supports and valuable feedbacks.

Finally, I would like to thank my parents, family, and friends for the endless support and prayers.

Stockholm, November 2017
Uri Arta Ramadhani

Contents

List of Figures

List of Tables

List of Acronyms

3GPP 3rd Generation Partnership Project

BS Base Station

Capex Capital Expenditure

CQI Channel Quality Indicator

EPC Evolved Packet Core

E-UTRAN Evolved Universal Mobile Telecommunications System Terrestrial Radio Access

FION Fully Integrated within the Operator Network

LTE Long Term Evolution

METIS Mobile and wireless communications Enablers for Twenty-twenty (2020) Information Society

MOS Mean Opinion Score

O&M Operation and Maintenance

OFDM Orthogonal Frequency Division Multiplexing

Opex Operational Expenditure

OTT Over-The-Top

PDCCH Physical Downlink Control Channel

PDSCH Physical Downlink Shared Channel

PRB Physical Resource Block

PSNR Peak Signal to Noise Ratio

QoE Quality of Experience

RRM Radio Resource Management

SNR	Signal to Noise Ratio
TBS	Transport Block Size
UE	User Equipment
W-CDMA	Wideband Code-Division Multiple Access

Chapter 1

Introduction

In this chapter, a general introduction to the background area of the thesis and the research problem that needs to be addressed will be presented. This chapter also states the purpose and goals of this Master's thesis, together with a brief explanation of the research methodology selected for this project. The delimitations and the structure of the thesis are described at the end of the chapter.

1.1 Background

In the past decade, access to mobile communication has become a basic need for human activity. Service demand has grown significantly leading mobile network operators to continuously improve their infrastructure in order to provide higher capacity. According to Ericsson's traffic measurements, in Q1 2017, the traffic generated by mobile phone users had increased almost ten times from the year of 2012 [1]. However, there has been a change in the service demanded by users. In recent years, users tend to access data services rather than voice services. Mobile data traffic in Q1 2017 has grown 70% from the same term in 2016 [1]. Moreover, the popularity of Over-The-Top (OTT) messaging platforms disrupts the mobile operators' revenues and margins, as mentioned in EY's white report [2].

To boost revenue, mobile operators are competing to offer an attractive data bundle to their customers. Price wars are inevitable between operators and this drives high churns rates in the mobile communication market [3]. Furthermore, according to Arthur M. Hughes [4], the average annual churn rates experienced by telecommunication companies are between 10% and 67%, which mostly driven by customer dissatisfaction. With the low growth of mobile subscriptions weighing on revenue growth [5], retaining current customers becomes a requirement for the mobile operator to survive in a competitive market. According to EY's white report, 68% of telecommunication industry experts focus on customer experience management to boost an operator's customers' loyalty[2].

Quality of Experience (QoE) is a novel approach to attain a comprehensive understanding of the customer's experience and also an interesting topic for researchers who seek to improve customers' loyalty. Hence, maintaining the user's QoE becomes a crucial concern for a mobile operator who wants to retain their customers and in turn assure the operator's financial stability. By integrating QoE into mobile networks, the user's satisfaction level is expected to be improved and customer retention can be better managed.

In work by E. Liotou, there are three potentials opportunities driven by incorporating QoE to mobile network: "*(a) to increase the loyalty of the customers and to decrease customer churn, (b) to drive business and operations and Customer Experience Management solutions, and (c) to cut costs by identifying and exploiting the non-linear relationship between QoS parameters and the perceived QoE*" [6]. From these potentialities, incorporation of QoE into the network may have impacts on the operator's business model, specifically in optimizing QoE utilization and assessing its benefit in economic perspective.

Looking at the impacts of QoE incorporation into the network operations on the operator's future business and the fact that the mobile operator highly depends on their capital investment to operate their business, an economic evaluation is needed to identify QoE's financial effect. Therefore, this Master's thesis investigates the impact of embodying QoE to mobile network technology on the mobile operator's profitability. This work provides information about one potential mechanism to control QoE in the network operation and then exploits user's level of satisfaction based upon the effect of this mechanism to derive QoE's implication on the operator's business.

1.2 Problem

As described in the previous section, nowadays mobile operators are in a complex situation with various challenges they need to manage, such as continuously increasing mobile traffic demand, slow growth in new subscriptions, and revenue disputes with OTT players. In order to survive in the competitive telecom market, the operator needs to preserve their customers' loyalty by maintaining their users' satisfaction. As operators focus on increased loyalty and spending [2], QoE-centric network management can be a solution for the mobile operator to tackle the challenges considering its potentiality to improve customers loyalty, as identified by E. Liotou [6]. The results of previous studies have shown an improvement of user experience by developing radio resource allocations that are aware of QoE, such as the work conducted by Essaili et al. [7], J. Kim, G. Caire, and A. F. Molisch [8], and Sing et al. [9].

According to ITU-T G.1080, a considerable number of factors that contribute to QoE can be classified into two main components: those related to Quality of Service (QoS) and those related to human components, such as emotions, service billing, and experience [10]. For a long time, a techno-centric approach based on QoS metric (e.g. delay, jitter, throughput, and bit error rate) has been used to measure the QoS delivered to the user, as stated by E. Liotou [6]. Further, he acknowledged that QoS metrics alone are unable to account for QoS at the level representing a user's experience. By incorporating a QoE-centric approach to network operations, there may be a shift from a techno-centric to a user-centric paradigm in customer experience management.

On the other hand, A. Perkis, P. Reichl, and S. Beker concede that the shift towards a user-centric paradigm poses consequences on economic and business models in the telecom market [11]. A comprehensive study of the QoE impact on business perspective is needed by a mobile operator as one of the business actors in the mobile industry. Furthermore, to run their business, each mobile operator must make continuous investments to update their network and deploy new technologies [12].

Although previous studies have been conducted to investigate QoE, the main focuses of these studies were on technical aspects, specifically on the potential for QoE-based resource scheduling to improve the performance of the delivered service. Other researches studied general business analysis, without specifically assessing the effect of QoE on the operator's finances. Thus, a study to investigate the potential benefit of utilizing QoE in resource allocation with regard to investment cost and profitability is essential since the decision to deploy a new technology has a major impact on the operator's finance. To be more relevant, the profitability of existing resource allocation is measured for comparison.

Based upon these findings, a problem statement arises in the form of: *Does QoE-based resource management offer greater profitability compared to the conventional approach?*

1.3 Purpose

The purpose of this thesis project is to evaluate the difference in profitability between two different approaches to resource allocation management: QoE-based resource scheduling and a conventional scheme (specifically proportional fair (PF) scheduling). The difference will be monetized by considering the predicted revenue loss due to customer churn and the deployment cost. The result may provide elements the mobile operator needs to consider when forecasting the profitability of implementing QoE-based resource management.

1.4 Goals

The main goal of this thesis is to make a quantitative comparison in terms of profitability between applying QoE-based resource allocation and PF scheduling based only on network performance. This goal has been divided into the following two sub-goals:

1. Compare the performance of the QoE-based resource scheduling and PF scheduling, and

2. Estimate the revenue loss due to churn by customers who experience unacceptable service quality.

1.5 Research Methodology

To answer the research question, the selection of methods were established by considering the portal of research methods and methodologies proposed by A. Håkansson [13]. Quantitative research is conducted in this project in order to have a profitability comparison of the two schedulers. Positivism is chosen as the underlying philosophical assumption since we will observe the performance of the two schedulers and then calculate their impact on the mobile operator's profitability. Further, the experimental research method (specifically simulation) was selected as we want to find the causal relationship between variables in order to investigate the performance of the two schedulers. To verify the research question, we use a deductive approach since the conclusion of the research will be derived from causal relationship that is found between the variables, based on the results of simulations.

Based on the nature of research problem, to complete the project we conducted the research by using both technical and economic approaches. In the technical part, the performance of the two considered radio resource management (RRM) schemes were evaluated. This data was then utilized as the basis for cost analysis to measure the profitability in the economic part.

The two alternative RRM schemes considered in this project will be simulated in a simplified Long Term Evolution (LTE) network. Proportional Fair (PF) scheduling is used as the current resource allocation scheme in the simulation since it is widely used in existing wireless networks [14]. A comparative study of QoE-based resource schedulers lead to the selection of an allocation scheme that considers buffering percentage as a QoE metric when making scheduling decisions. This second RRM scheme was chosen as it guarantees fairness between different users' satisfaction.

The performance of both schedulers is evaluated based upon Mean Opinion Score (MOS). MOS is a quantitative human perception measure of streaming video behavior. In this thesis, MOS is based on an objective test which considers buffering time as the video quality metric. Although subjective testing is a benchmark for the objective test, such subjective testing is time-consuming and expensive means to measure user satisfaction. As a result, researchers have designed objective tests that have a high correlation with subjective tests [15]. Furthermore, F. De Rango, et al., stated that subjective methods are limited and impracticable during network design [16]. For these reasons, an objective test was selected rather than performing a subjective test using human subjects.

The simulation, includes different number of base stations in network design, generates user QoE level as outcomes. Based on the simulations, the profitability of deploying PF and QoE-based resource schedulers is computed by considering the revenue loss due to customer churn and deployment cost of implementing the two different RRM schemes.

1.6 Delimitations

There are different type of services offered by the mobile network operators, ranging from voice, text messages, web service, to multimedia content. To measure user's satisfaction, the subscriber's QoE using all of these services should be examined. However, due to the limited time available for this study, this project will focus on multimedia content services, specifically video streaming. The selection of video service is due to the dominance of video demand in mobile traffic as much as 50% of total traffic in 2022 [17].

The simulation considers only MPEG-4 compressed video, i.e., it assumes that all video is carried in MPEG-4 format. MPEG-4 format video was selected as it is able to deliver higher video quality at lower data rates and with smaller sized files. Also, MPEG-4 is supported by almost all video players in the industry [18]. The details of the encoding and decoding process of video streaming are outside of the scope of this thesis. In addition, in this thesis, the quality of the user's experience is assumed to be simply a function of the buffering time (i.e., the amount of time it would take to play out the buffered data at the user's device or interruption duration experienced by the users). This assumption was taken from real-time behaviors of a service that have impacts on QoE [19].

Due to the complexity and limited duration of the project, the scheduling algorithms are simulated in a simplified LTE network with the users at fixed positions. For the same reasons, interference, carrier aggregation, and noise are *not* considered in the simulation. These limitations may affect the simulation results in a comparison with a real LTE network and these limitations will be discussed in Section 5.3.

1.7 Structure of The Thesis

This Master's thesis is organized into 6 chapters. Chapter 1 presented the motivation and the purpose of this thesis. Chapter 2 describes the background theory about the QoS and QoE, streaming video, and LTE networks. Chapter 3 presents the research methodology used in this project. Chapter 4 describes how simulation was conducted and the parameters considered in the simulation. Chapter 5 presents the results collected from the simulations and the cost analysis based on these results. Chapter 6 summarizes the thesis project and suggests possible future work building upon this project.

Chapter 2

Background and Related Works

This chapter provides information about operator's current situation related to QoE, as explained in Section 2.1. Explanations of QoE-based resource allocation and how to evaluate user satisfaction are also presented in Sections 2.2 and 2.3 respectively. Since we will investigate the performance of QoE-based resource allocation in a simplified LTE network when used to provide a streaming video service, background theories of streaming video and resource allocation in LTE are explained. A thorough literature survey highlighting recent studies that support this project are presented in Section 2.7.

2.1 Challenge in Mobile Communication Industry

In recent years, daily human life cannot be separated from mobile communication technology. Access to mobile communication ranges from social life to personal affairs, for example, it ranges from entertainment applications to confidential bank transactions. The wide coverage of this mobile communication implementation has driven a significant traffic growth in mobile communication networks. In recent article, Ericsson reported that the increase of total traffic in mobile networks is 70% between the end of Q1 2016 and the end of Q1 2017 [1]. Furthermore, Cisco white paper predicted increase in mobile data traffic to 49 exabytes per month of by 2021, seven times higher than in 2016 [20].

The increase in the amount of traffic is in line with the burden of this data load on the mobile network. A traffic load that exceeds the capacity of a mobile network may cause congestion and degrade the performance of mobile services. One possible solution to solve this problem is to increase the capacity of the network by building additional mobile network infrastructure (e.g., base transceiver stations). However, adding more base transceiver stations cannot easily be done since mobile network operators would need to make a huge investment in building new network infrastructure. Aside from the increase in traffic, mobile network operators are also experiencing a slow growth of revenues. In western Europe, B. el Darwiche et al. stated that Average Revenue per User in the telecommunication industry is declining as many as 6%, from 2011 until 2016 [21]. A GSM Association (GSMA) Intelligence report states similar conclusions and gives several explanations for this slowing of revenue growth, such as low growth in new subscriptions and increasing competition [5].

The reduction in mobile revenues is also caused by massive traffic data from OTT messaging platforms, such as Whatsapp, Skype, and Facebook. With the decline of traffic load from voice and text messaging, mobile network operators are losing potential revenue. All of these reasons for slow growth in revenue further limit the network operator from building more network infrastructure.

The increasingly competitive market in the telecommunication industry has become another challenge for network operators. Since the reduction in revenue is experienced by most network operators, they are all striving to gain as much revenue as possible, hence a price war between network operators is unavoidable. They compete to provide the best offerings to mobile users. This situation causes high rates of customer churn [3]. Customer churn happens when a customer terminates his/her subscription with one network operator and starts to use service from another network operator. In other words, customer churn is related to a lack of user loyalty to a service of the mobile network operator. One action that can be taken by a network operator to avoid customer churn is to maintain the customer's loyalty to continue using their service.

Network performance used to be the only essential element that impacts the mobile user's loyalty [22]. However, there has been a transformation in both usage behaviors and users expectations, as the evolution of mobile applications and the increase in video traffic have caused a change in customers' loyalty. This concept was mentioned in Ericsson's Consumer and Industry Insight report which concluded that the mobile user's loyalty is impacted by their mobile broadband experience three times stronger than strategy improvement in pricing and offerings[22]. Mobile broadband experience depends on the user's satisfaction in many aspects of specific types of service (for example web page and video load time). In this case, the mobile network operator needs to find cutting-edge solutions to maintain customers' loyalty.

In order to address these challenges and survive in the competitive market, mobile operators may consider many possible solutions, such as adopting a new business model, acquiring new customers, and maintaining their customers' loyalty to avoid customer churn. However, according to K. Saleh, the cost with consideration to time and spent resources to attract a new customer is more expensive than to keep an existing one [23]. Based upon these findings, mobile operators should focus on their users' experience in order to preserve their customers' loyalty and avoid customer churn, which in turn aims to prevent revenue reduction.

A user's experience refers to his/her perception towards the user's demand for a service. Hence, in order to satisfy a user, the network operator should provide a service that at least meets the expectation of the user [24]. The user's experience may be effected by many factors, depending on the type of the service. For audio service, a drop call is one of the parameters having a high impact on the user's experience. A dropped call may be caused by congestion in the network. For streaming video service, one of the parameters that effects the user's experience is buffering time [25]. Buffering time is the (limited) duration of video files stored in a buffer which may cause an interruption in video playback when this buffer is exhausted and additional video content has not been placed in the buffer. In this sense, when a user streams a video file, the amount of resource allocated to the user will influence the buffering time and later involve in the quality of user experience.

Many researchers, for instances A. Essaili et al. [7], V. Ramamurthi et al. [26], and J. Kim et al. [8], have studied new approaches to resource allocation that are aware of the user-centric parameters in order to improve users' experience of a streaming video service. This will be described in Section 2.7. These studies have shown positive results in the improvement of delivered service quality. These results indicate the possibility for mobile operators to adopt these new approaches in order to improve their customers' satisfaction which in turn would help to maintain their customers' loyalty. However, the decision to deploy a new technology requires deliberate consideration by the mobile operator since it needs costly capital investments to implement such new deployment. Comparing business aspects of deploying a user-centric RRM scheme with a traditional RRM scheme is important. Therefore, conducting a study that investigates the impact of deploying user-centric RRM scheme from a business perspective will provide relevant insight to a mobile operator with regard to their consideration of deploying a user-centric RRM scheme in their network.

2.2 QoE-based Resource Management

Quality of Experience (QoE), refers to a user's perception of a service. QoE has been a popular topic among researchers and practitioners. A Qualinet white paper defines QoE as "*the degree of delight or annoyance of the user of an application or service. It results from the fulfilment of his/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*" [19]. The ITU-T P.10/G.100 defines QoE as "*the overall acceptability of an application* *or service, as perceived subjectively by the end-user"* [27].

There are many factors that influence the users' perception of a service or application. Those factors may depend on the types of service. For example, for an audio service, the users will not be concerned about variation in image resolution, whilst for a video service, image resolution may be an important factor for the user together with the audio sampling and rendering process. Not only will the system's performance characteristics effect the users' perception of the quality of a service, but so can cost, cultural background, motivation, emotional state, and other subjective factors.

The ITU-T G.1080 classifies a number of factors that contribute to QoE into two main components: those related to QoS and those related to the human component [10]. However, in conventional network management, mobile operators as service providers only focus on various QoS metrics when considering making improvements to their networks, hence they do so without regard to the user's experience. Meanwhile, it is widely known that the user's experience is an important factor in maintaining the customer's loyalty. Based on this awareness, researchers have been studying how to incorporate QoE within the wireless infrastructure, specifically in a resource allocation scheme.

Typically, there are two approaches in QoE-based resource management: Fully Integrated within the Operator Network (FION) and OTT approaches [28]. In the FION approach, a base station is aware of the QoE metric status of the mobile terminal and uses this information to make resource allocation decisions. For the OTT approach, it is the content server that will evaluate the content processing and QoE metric status, then use this information for allocating resources. In this project, the FION approach is used since it is more suitable for the research's purpose, which is to evaluate the benefit to the operator of deploying QoE-based network architecture.

The FION approach is depicted in Figure 2.1. It should be noted that the communication between the network and a user equipment (UE) occurs in both directions i.e., from the network to a user and from a user to the network. A user who intends to access a certain type of service sends a request for resources to a base station over an LTE network. The base station then will send a request for Channel Quality Indicator (CQI) information. A QoE agent located in the base station sends a request for information of the (current) QoE metric status to the user. The user, through a Client Information Reporter that is located in the mobile terminal, will report to the base station and QoE Agent the CQI and QoE metric status information of the connected user. The scheduler uses the CQI, the user's data rate and average throughput, and QoE metric information to give weight to the user when determining the number of bits that can be transmitted when delivering the video file. Afterwards, the base station will compare the weight of all users simultaneously connected. If a user has the highest weight, then that user is selected to be the scheduled user and allocated radio (channel) resources.

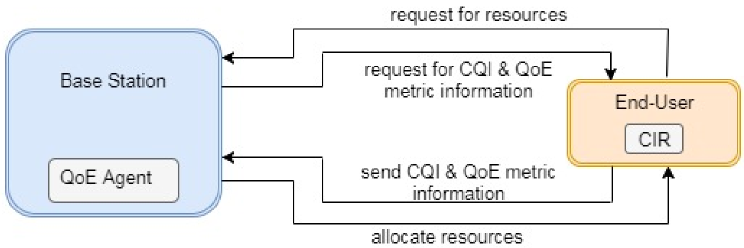


Figure 2.1 A system of QoE-based resource management

With the awareness of the user's QoE metric status, the scheduler is supposed to be able to assure satisfaction for each user by optimally allocating its resources based on the collected QoE metric information. For example, for a user who experiences frequent interruptions when streaming a video, the scheduler needs to increase the priority of that user in order to improve his/her QoE. Since we consider only a streaming video service in this project, a buffering time or duration of interruption is selected as the QoE metric status that should be considered by the scheduler when allocating resources.

2.3 User's Satisfaction Measurement

Practitioners in the media industry try to describe the level of the user's experience in the terms that are widely accepted and easily understood by the professionals from various fields. ITU-T P.800 suggests recommended methods for testing the quality level of the user's perception. One of these methods is Absolute Category Rating that consists of five-point scales which maps the rating scale to the degree of satisfaction, from scale 1 for a bad quality, to scale 5 for an excellent quality [29]. This method is usually applied in measuring the user's perception of an image or video sequence.

MOS, a variant of Absolute Category Rating testing, is a popular measurement method that gives numerical values to describe the level of satisfaction quality for the various type of service, including audio, video, images, and interactive games. According to ITU-T Recommendation P.10/G.100, MOS is defined as the scale assigned by a subject representing his/her opinion of the performance of a system [27]. However, MOS is not only utilized to express the result from a subjective test but is also used to provide a numeric outcome from an objective test. Although subjective testing seems to be more eminent in terms of external validity when testing subjects with different demographic characteristics, it requires considerable time for the experiments, hence it has a high cost [30]. Furthermore, subjective testing is infeasible in practice for real-time monitoring, such as for the purposes of QoE-based network management. Hence, an objective test is a crucial alternative method to assess the quality of user's experience.

ITU-T Recommendation J.247 has proposed three possible methodologies for measuring QoE through an objective test: the full-reference model which requires full access to a reference file, the reduced-reference which has limited information about the reference source, and the no-reference model which does not necessarily need knowledge of reference file [31].

Overall, all of these three methodologies are possible for the various type of applications, such as internet multimedia streaming, video telephony, and mobile video streaming over a telecommunication network. The full-reference supposed to provide a result with high accuracy. However, this model may only be applied if one has access to both end systems as it requires the source file as a reference. Hence, for QoE-based network management implementation, the no-reference model, which does not necessarily need knowledge of the reference file, can be the appropriate method to measure the user's QoE level.

2.4 Mobile Operator's Perspective on Resource Management

The foremost goal of the business run by mobile operators is to gain revenues from the service they offer to their customers. In the recent mobile communication market, customer retention has become an important business strategy for mobile operators. With the maturity of mobile telecommunication market, the ability to maximize the number of satisfied users attracts more subscribers and improves customer retention. The task for the mobile operator is to manage its network resources in order to improve the satisfaction of the user's experience and further maintain customer's loyalty. This intention can be implemented by enhancing the mobile network from a technology-centric to user-centric paradigm, since a QoS metric is no longer adequate to represent a user's experience, as explained in the previous section.

Recently researchers have shown the ability of QoE-based resource allocation to improve the quality of a user's experience, and this approach can be an alternative solution in a customer retention strategy. The advancement of mobile network technology to QoE-based resource management influence the operator's investment and operational cost. Further, according to A. S. Kyriazakos and G. T. Karetsos, in a mature network, profit can be increased by the optimization of resource usage which is supported by optimization tools whose license prices may exceed the infrastructure's cost [32]. They also mentioned that the ability to manage the resource allocation for fulfilling 1% more of the offered traffic would have an impact of significant increases of revenue, in mature networks with millions of subscribers. The enhancement of using Orthogonal Frequency Division Multiplexing (OFDM) and carrier aggregation in 4G technology is one example of enhanced resource management enabling the network to provide higher capacity and hence increase the number of users being served.

Based upon the findings about the impact of resource management on the business perspective for mobile operators, it is noteworthy to investigate the effect of deploying a QoE-based resource allocation scheme on the mobile operator's profit. This study is important as it will examine the necessity of adopting a new resource allocation approach given that the mobile operator has to make a huge investment in such a long-term deployment.

Since we are interested in improving the user's satisfaction in order to maintain the loyalty of customers, we focus on the relationship between profitability and customer churn. According to a working paper by A. Lemmes and S. Gupta, one aspect that influences the profit of a retention action is the value of a customer to the company [33]. The value of a customer may be interpreted as the money spent by the customer for the product or service he/she gets. In this project, the profitability comparison of utilizing conventional and QoE-based resource scheduler will be measured with regard to the loss of customer value experienced by the company due to customer churn. A detail explanation about this profitability measurement will be discussed in Section 3.3.3.

2.5 Video Streaming

Nowadays, video streaming has become a popular media service and is commonly used by fixed and mobile broadband users. The increase in aggregate of video traffic by mobile users motivates the selection of video streaming access as the type of service simulated in this project. To understand more details about media streaming, it is necessary to understand streaming-related terms that support an sufficient media streaming service [34]. These terms include:

1. CODECs

   CODECs are media encoding and optionally compression techniques that consists of two components, which are an encoder and a decoder. The encoder will encode and perhaps compress the file while the decoder will decode the file when being played or displayed by the user. Lossy CODECs will discard unnecessary data and lower the resolution to reduce the file size. There are different CODECs for various type of files. For example, JPEG is a frequently used CODEC for an image file, audio files will often be compressed by an MP3 CODEC, and additionally there are H.264, Windows Media, and MPEG-2 CODECs for video files.

2. Bit rate

   Bit rate is a number of bits in one-second worth of a video file, typically expressed in kilobits or megabits per second. As the number of bits in one pixel impacts the dynamic range of the video, a lower bit rate video will result in a degraded quality of a video, assuming the frame rate, resolution, and picture size are equal. Moreover, it is not simply the number of bits per pixel, but the encoding across multiple pixels in a frame and across frames in a sequence of frames that matters.

3. Frame rate

   The frame rate is the number of still images (frames) that are played in one second. Commonly, video is delivered at 24 frames per second or lower. For example, video may be rendered at 15 frames per second to reduce the bandwidth required.

There are several alternatives that can be used to deliver video over the Internet, such as streaming, progressive download, and adaptive streaming. In streaming techniques, when a user clicks a play-button on a website, the video file is delivered from a streaming server, and later be played via the user's computer or other device. In progressive download, instead of being delivered via a streaming server, the video is distributed by a web server. The streamed video is not directly played via the user's computer/device, but the video file is stored in a user's local hard drive (or other buffer). This buffer acts as temporary storage so the video player can play the video smoothly, even though the user's connection bandwidth is below the video bit rate at some points in time. After a user clicks the play-button, he/she needs to wait for a moment until the first buffer's of media content is loaded from the video file in order for the player to begin to display the video. Adaptive streaming enables the use of multiple streams to deliver the video based upon the user's connectivity. This technique requires the encoder that can encode a single source video at multiple bit rates. At first, the user's bandwidth is monitored in real time, and then the quality of the video stream is adjusted accordingly. In adaptive streaming, a buffer is employed to assure that the player can display the video smoothly. In practice, Youtube has switched from progressive download to adaptive streaming for delivering video.

In the QoE-based resource allocation simulated in this project, the buffer storage information acts as QoE-metric that the scheduler needs to aware of, when selecting a user to be assigned resources. If the number of frames in the buffer is below a minimum amount, then the user will start to experience interruption when playing the video.

2.6 Resource Allocation in LTE Network

In the simulation for this project, video files are delivered to the user through allocated radio resources. The radio resource allocation scheme considered in this thesis is LTE's radio resource allocation in the existing LTE network.

In LTE, the smallest allocated resource is a Physical Resource Block (PRB). The downlink transmission is based on OFDM using a cyclic prefix that is utilized to prevent inter-symbol interference [35]. The OFDM sub-carrier spacing is 15kHz. A PRB consists of 12 sub-carriers by 7 OFDM symbols which totals 84 modulation symbols. These 84 modulation symbols are set in one slot within 0.5 ms, thus two slots are equal to 1 ms or (one subframe/Transmission Time Interval). A physical-layer frame structure consists of 10 subframes.

In each subframe, there is a downlink control channel (PDCCH) and a downlink data channel (PDSCH). The PDCCH conveys control information for each terminal. PDSCH is used for data and multimedia transport. In addition, PDSCH multiplexes the data of all terminals in the network and transmits it using a unique set of resources. The base station schedules the downlink transmission of all terminals and uses PDCCH to reserve PDSCH resources [36]. The number of bits allocated to the user in each allocation depends on the Transport Block Size (TBS) and the number of RBs. The number of RBs also depends on LTE channel bandwidth as specified by 3GPP. The base station will select a Modulation and Coding Scheme (MCS) Index based on the Channel Quality Indicator (CQI) reported by the user. However, the association between MCS and CQI index is vendor specific [37]. Given a MCS Index, the base station can obtain a TBS Index. Then the number of bits delivered to the scheduled user is obtained by mapping the TBS Index and number of RBs according to the LTE ETSI TS 136.213 specification.

2.7 Related Works

A literature study was conducted to select appropriate methods for this thesis. Previous researches about QoE-based radio resource management is presented in Section 2.7.1. Section 2.7.2 presents the studies about how to measure the user's satisfaction level based on particular QoE metrics. Studies about techno-economic aspects of cellular network planning are depicted in section 2.7.3. Studies of QoE-based RRM and QoE measurement are explored to build the simulation model which belongs to the technical part of this project. The outcomes of the simulations are analyzed in terms of profitability. The techno-economic studies are used as references to measure the profitability of QoE-based resource scheduler and PF.

2.7.1 QoE-based Radio Resource Management

Singh et al. [9] proposed QoE-aware resource allocation management which allows the network operator to enhance their capacity for video content. They introduced re-buffering percentage as one of the parameters to ensure the fairness of resource allocation in conjunction with an adaptive streaming framework. Other parameters were also considered to upon the allocated user, including frame rates, number of frames, and instantaneous data rate. The performance was evaluated in terms of the number of users who achieved satisfaction above a certain QoE threshold. This resource allocation algorithm has the benefit that it increases the capacity in terms of the number of users by utilizing both QoS and QoE parameters.

Essaili et al. [7] also utilized an adaptive streaming framework to deliver HTTP video via an LTE network. They proposed a resource allocation scheme which jointly considers buffer level and dynamic adaptive streaming over HTTP (DASH). In their proposed method, they had a QoE optimizer and assumed that the proxy server could collect buffer level information from the users. Performance was evaluated in term of MOS values based on Peak Signal to Noise Ratio (PSNR) for different scenarios. They also compared their result with those obtained from a subjective test. Although they considered buffer level as one parameter of a QoE-aware resource allocation scheme, play out interruption was not observed at the client during the experiment. Furthermore, they only considered one LTE cell with 8 users in the simulation, hence it is not represent of a real network situation.

Ramamurthi and Oyman [26] utilized the HTTP Adaptive Streaming (HAS) framework in their resource allocation algorithm and aimed to constrain the probability of re-buffering. They considered received, played, and buffered video duration and set thresholds to define specific conditions during the experiment, including steady state, transient state, and re-buffering state. Given their objective of avoiding re-buffering, they set required conditions upon on the download time of a video segment, media duration, and tolerance parameter. Although their proposed algorithm performed better than the other algorithms it was compared with, the probability of re-buffering was slightly different than that obtained from Singh's work. Due to its higher complexity, the proposed algorithm might have degraded performance if it was applied with more users since the time computation may be longer.

J. Kim, G. Caire, and A. F. Molish [8] investigated the performance of centralized and distributed scheduling for device-to-device video delivery. They developed a distributed scheduling algorithm by introducing specific weights for video-streaming. The pixel dimension of a video chunk, hops of Device to Device links, and pre-buffering time were the input parameters of the algorithm, which then finds the set of links that maximize the sum of weights over all possible independent hops. The performance of the algorithm was evaluated by measuring the PSNR and number of stalls, then compared this with other resource allocation schemes, such as FlashlinQ [38]. However, video content behavior was considered less important by this algorithm when deciding upon the allocated user. Furthermore, the video users are usually more sensitive to interruption during playback rather than the picture distortion of the video, hence they are more tolerant of pre-buffering time than re-buffering during the playback.

2.7.2 QoE Model

Q. Huynh-Thu and M. Ghanbari [39] used a no-reference temporal quality metric to model the impact of frame freezing on perceived video quality. This metric belongs to the parameters of video quality assessment algorithm in ITU-T Recommendation J.247 Annex C. For a no-reference approach, frozen frames were identified without reference video, by using only the processed video sequences. A frame was marked as frozen in the playback if the MSE between video frames are below a threshold, which is set as 1. The duration of a frozen frame could be obtained from the histogram representing the distribution of individual freeze events. The frozen duration was then translated to an MOS quality metric by using additional parameters determined from subjective data. Their experiment showed a high correlation between subjective tests and model prediction. Their proposed no-reference model has the benefit that it can be applied to a streaming video delivery since is not affected by the absence of full-version video.

M. A. Usman, M. R. Usman, and S. Y. Shin [40] utilized the no-reference method to detect dropped video frames in live video streaming. The dropped video frame was identified by evaluating the video in binary format, instead of RGB color space, with the aim of reducing computational time. Temporal information was obtained in the first stage of the examination, which then was used to detect dropped video frames in the second stage. Two thresholds were considered in the algorithm to consider both high and low motion videos. The performance of the algorithm was shown in terms of number of frames and their temporal information. However, there was a trade-off in using two thresholds in order to tolerate the low motion video, as this occurred at the cost of missing dropped video frames.

Y. Xue, B. Erkin, and Y. Wang [41] assessed video quality perception using a no-reference model in order to evaluate the impact of frame freezing due to packet loss and late packet arrivals. They considered a number of features including number of freezes, freeze duration, inter-freeze distance statistics, and etc. Then they used a neural network to map the features to subjective test scores. Frame freeze was identified by examining the difference between sequence of video frames. The features of the video were then extracted from the frame freeze location. Using a neural network structure, the users' perception score was obtained using a Sigmoid transfer function. The result of the predicted scores obtained from the neural network was similar to the quality scores from the subjective test. However, the proposed algorithm required an exhaustive search in order to select the number of hidden nodes in the neural network and number of features. Furthermore, in their work, 13 features were extracted to obtain the quality scores which might burden a packet during transmission.

Tran et al. [42] investigated the impacts of quality variations and interruption in a video streaming session on users' perception. The users' perception was represented as a MOS value based on the initial perceptual quality value, interruption factor, and initial delay factor. The initial quality could be estimated from the quantization parameter, frame rate, and/or resolution, which then were represented in a histogram. Their experiment showed that their proposed model had good performance compared to the subjective test. However, similarly to the Xue's work, to obtain an initial quality value, the algorithm needed 16 parameters which may affect the packet during transmission.

2.7.3 Techno-economic Studies

K. Johansson [43] studied the different cost and performance of multiple radio access standards and base station classes. With a premise that in the case of a non-uniform spatial distribution of traffic, the traditional measurement of coverage and capacity are not sufficient methods to compare the cost deployment of different networks. He proposed a general methodology to evaluate the total cost and capacity of a heterogeneous network for different environment scenarios.

J. Markendahl [44] investigated the cooperative strategies of mobile operators, and analyzed cost-saving strategies based on network sharing, spectrum sharing, and roaming. The study also included a number of case studies of different strategies to exploit new types of services and revenues. The analysis was conducted on three aspects: cost for deployment and operation; migration and co-existence with existing systems; and the type of business and revenue model for a specific service.

M. Varela et al. [45] emphasized the importance of Experience Level Agreements in the user-centric communication network to sell service quality to the user, rather than Service Level Agreement as used in the techno-centric network. They identified several issues (framework, language, and marketing) related to Experience Level Agreements that need to be worked out when the service quality has completely changed from techno-centric perspective to user-centric approach.

L. Ballesteros [46] investigated the impact of integrating QoE in the mobile network on the business model by analyzing scenario planning that considered net neutrality regulation. The study showed that with strict net neutrality regulation, there is a limitation of what techniques can be used to apply the QoE-based business model. While, for liberal net neutrality regulation, there are opportunities for new business model based on QoE differentiation.

2.8 Summary

With the complex challenges faced by mobile operators in recent years, the operator's business strategy has focused on maintaining customers' loyalty. A possible solution is an improvement in customer retention by preserving a user's QoE. In the concept of QoE, there is a shift from the technology-centric approach to the user-centric approach. Satisfaction of a user is driven by the user's expectation rather than network performance. According to recent studies, incorporating a QoE metric in radio resource scheduling is a potential procedure to increase mobile users' satisfaction. However, the previous researches only focused on the technical side of how to improve the user's QoE level and studied the general impact of QoE on mobile operator's business ecosystem. On the other hand, to deploy such a new technology in the network, mobile operators need careful evaluation of how the deployment will impact their business, specifically in terms of profitability. Based on this understanding, we attempt to address the research gap regarding the impact of QoE on mobile operator's profitability.

Chapter 3

Methodology

This chapter provides the description of research framework used to conduct the project. The proper research methods and methodology were selected in accordance with the research's intention. The description of the research process is explained in Section 3.1. Section 3.2 presents the research paradigm for selecting the methods used in the project. The detailed solution design to address the research problem is presented in Section 3.3, which includes the experimental design and data collection method. The data collected from simulation will be analyzed to generate results to answer the research problem.

3.1 Research Process

This thesis work includes a technical aspect of RRM and impact of deploying QoE-based RRM on mobile operator from an economic aspect. To complete the project's overall task, the research was conducted through four stages: problem identification, literature study, solution design, and solving the research problem. Figure 3.1 shows the connection of the research stages throughout the research process.

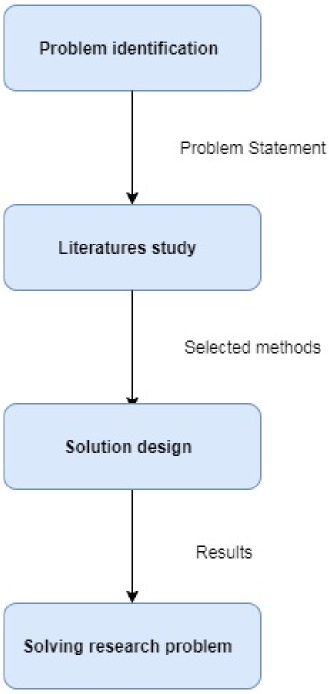


Figure 3.1 Research process framework

Through a background study and discussion with an expert [1] who understands the role of QoE in the mobile communication network, the challenge of mobile network operators in deploying QoE-based resource management was figured out. According to the literature survey, most of the previous conducted research, such as the works conducted by A. Essaili et al. [7] and V. Ramamurthi and O. Oyman [26], focused only on the technical aspects of incorporating QoE metric in the mobile communication network. Although these studies showed better performance of QoE-based resource management compared to other RRM schemes, there is a research gap about the impact of deploying QoE-based resource management from the business perspective, especially when it relates to the profitability factor for the network operator. The closest related work was done by L. Ballesteros [28] who studied the impact of using QoE on a mobile operators' service provision.

All of these findings led to the identification of a research problem which questions the effectiveness of deploying a QoE-based RRM scheme for a mobile network operator from an economic point of view. In order to make it easier when solving the identified problem, the research problem focused on a problem statement: *Does QoE-based resource management offer greater*

[1] Dr. Luis Guillermo Ballesteros, a former project manager on the incorporation of QoE in mobile networks from a technical, regulatory, and business perspective and built partnership with vendors and mobile operators

profitability compared to the conventional approach?

Once the identified problem is solved, the result is supposed to bring a substantial contribution of knowledge to the mobile network operator. Since the deployment of mobile communication infrastructure demands a huge investment, careful consideration is required when it comes to network planning decisions. When a mobile network operator has a comparison of profitability between deploying QoE-based resource management and existing RRM, then the necessity of applying a QoE-based resource scheduler can be examined.

After the problem statement was formulated, we identified profitability based on user satisfaction level as a variable that exhibits distinguish performance between QoE-based resource management and existing RRM. Based on this result, we conducted an extensive literature study and examined related works in order to explore a possible research method to solve the problem. The descriptions of this literature review and related works are presented in Chapter 2.

Given the research objective, problem statement, and conceptual understanding from the literature study, a quantitative research methodology was chosen. The reason for selecting quantitative research was because we intend to measure a variable, profitability driven by the users' satisfaction level, to answer the research problem. Then, based on quantitative research, we developed a solution that included technical measurement and economic analysis. In this stage, we devised a mechanism to obtain the comparison of profitability which depends on the users' satisfaction level comparison between the two different resource schedulers. The detailed information of the design of this solution are described in section 3.3.

3.2 Research Paradigm

Since a quantitative research methodology was used in this thesis, research method and strategy were devised based on a quantitative study. We followed the portal of research methods and methodologies proposed by A. Hakansson [13] to develop a solution for this project. The steps for completing the solution are illustrated in Figure 3.2.

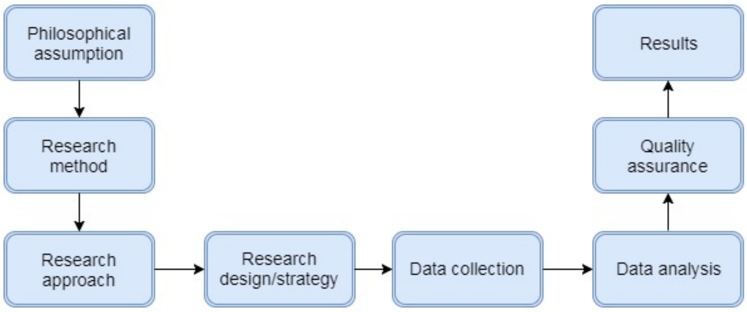


Figure 3.2 Research paradigm

Positivism is a suitable philosophical assumption for this project for the reason that we intend to gain knowledge about the profitability comparison between two schedulers through simulation and observation of a quantifiable variable. The result of the positivism assumption is driven by statistical analysis, hence the role of the researcher is limited to data collection. Furthermore, the observation is independent of human interest of the researcher.

We chose experimental research as the method for this project since we want to find the impact of QoE-based resource management and an existing scheduling scheme on the network operator's profitability. For this experimental method, we identified variables that influence the profitability. As stated in the previous section, profitability will be measured based on churn rate of users. The churn rate is estimated according to the users' satisfaction level. The users' satisfaction level is expected to vary between the two schedulers since QoE-based resource management considers a QoE metric when allocating resources, instead of only using QoS metrics as the existing RRM does. Based upon these variables, experimental research is a suitable method to investigate causalities between them.

The chosen research approach for this project is a deductive approach, as we want to verify the answer to the research question using the quantitative method. The deductive method deals with measurable variables to test a hypothesis or answer a research question in the context of this project, hence the conclusion drawn in this approach is driven by collected data and explanations of the causal relationship between variables.

3.3 Proposed Solution

Looking at the research's goals, we devised a solution that combined technical measurement and economic analysis. The technical measurement included an experimental design which aimed to compare the performance of the QoE-based resource scheduler and PF. The performance of these RRM schemes was presented in terms of the users' QoE level. The collected data of the users' QoE level was then analyzed from an economic perspective to measure the profitability of the two considered RRM schemes. The detailed explanation of data collection, experimental design, and profitability measurement will be presented in the following subsections.

3.3.1 Data Collection

In order to answer the research question of this thesis, we need to collect data containing the users' satisfaction level. Since we are interested in measuring the satisfaction level of a user, a simulation was chosen as the data collection method in this project.

Ideally, to test the performance of RRM in a mobile network, various type of traffics should be considered. However, due to limited duration of this project, the type of traffic simulated is only video traffic. According to Ericsson mobility report, 60% of all mobile data traffic will be from video by 2020 [47]. Based on this data, we choose video traffic rather than other types of traffic, such as voice and web browsing, as we believed that it would be the most representative of the user's overall experience.

To evaluate the performance of a QoE-based resource scheduler and a PF scheduler when streaming a video file, Helenelund (as suburb of Stockholm) was chosen as the selected area for the simulation of a simplified LTE network. Helenelund is a part of Sollentuna municipality and consists of mostly resident urban area and workplace [48]. It is interesting to investigate the user's satisfaction of a video service in such an urban area, where traffic is denser. Hence, the demographic data of Helenelund was used in the LTE network dimensioning to set up the simulation.

According to the statistical data of Helenelund [49], the population of Helenelund is 11.100 inhabitants in an area of 9.25 km^2. To obtain the number of users that were used in the simulation, additional information was considered. Given the 39% market share of the largest mobile operator in Sweden [50] we assume there are 4329 users (of this one operator). Of these users, we assume 25% of them are simultaneously active, based upon the assumption of mobile traffic in Tokyo, as stated by R. Vannithamby and S. Talwar [51]. Furthermore, we assume that 50% of these active users are accessing video traffic according to Ericsson's statistical data [17]. Having made these assumptions, the number of users simulated in the experiment for the selected area was round up to 555 users.

3.3.2 Experimental Design

The experimental design contains steps carried out to obtain a performance comparison of PF and QoE-based resource schedulers in terms of the users' QoE level. We have identified several QoS metrics of the PF scheduler and the QoE metric of the QoE-based resource scheduler that will impact the users' satisfaction level.

In these simulations, the QoE-based resource scheduler and PF area were simulated using 555 users in Helenelund in a simplified LTE network, and QoE model was used to measure the degree of user satisfaction in terms of QoE level for the delivered video service.

In the following, we describe the experimental design that contains the QoE-based resource scheduling and PF scheduling, as well as the steps taken to obtain the users' satisfaction level.

PF Scheduler

In this research, PF scheduling represents the current resource allocation scheme used in modern wireless cellular networks [14]. The PF scheduler tries to maximize the network's throughput and provide all of the users with at least a minimal level of service at the same time [52].

In the PF scheduling algorithm, QoS metrics such as data rate and throughput are used to select a user who will be assigned the resources. After the eNode B receives a CQI report from a user,containing the requested data rate, R_i for user i, then it calculates the average throughput T_i for each user i in the past time slots. The fraction of the requested data rate and the average throughput of each user gives the weight of a user (according to Eq. 3.1). In a time slot t, the PF scheduler selects and assigns the resources to the user who has the largest weight $i*$.

$$i^* = arg\,max \frac{[R_i(t)]}{[T_i(t)]} \tag{3.1}$$

QoE-based Resource Scheduler

QoE-based resource scheduling is designed to be the solution to meet the future demand for delivering video service with satisfactory QoE levels. User expectations of a service may differ depending on the type of the service. Most of the video traffic in the current broadband network are streamed through adaptive streaming which stores the video files in a mobile device's buffer before being played via the playback application (app). Buffering is the state when the number of frames in the buffer is below a certain threshold while the app attempts to fill the buffer with video frames. This situation causes video playback to be stalled, hence a user experiences a moment of interruption because the video playback is unable to display new video frames. Therefore, the stall due to the buffering will impact the quality of the user's satisfaction. Hence, buffering time is one of the QoE metrics which plays an important role in determining the level of a user's satisfaction.

S. Sing et al. [9] investigated RRM based on the user's buffering status as the QoE metric. J. Kim, G. Caire, and A. F. Molisch [8] also have studied resource management for video traffic based on data rate and PSNR, and the performance was evaluated in terms of the number of stalls. However, data rate and PSNR are likely to be QoS metrics instead of a QoE metric, hence they are unable to present the video content's perception by the user. Therefore, the QoE-based resource management assessed by S. Singh et al. was applied in this research as it better suits the intention of this project, i.e., to study the benefit of deploying a QoE-based resource scheduler in the mobile network.

The QoE-based RRM algorithm used in the simulations is shown in Figure 3.3. After receiving the CQI report from a user, the scheduler determines the achievable data rate. The scheduler tracks user's average throughput from the previous time slot. Buffering time as a QoE metric is utilized as one of the parameters to make the resource allocation decision. This buffering time represented in terms of buffering percentage, $\mathrm{P}_{buff,i}$. Buffering percentage is the percentage of buffering duration to the actual watching time (i.e., the time when the playout occurs) [53]. Buffering time is obtained based on the feedback information from the user. Then, a fairness parameter, V_i is determined by two conditions as shown in Eq 3.2, with k being the total number of users.

$$V_i = \begin{cases} 1 + \frac{k \times \mathrm{P}_{buff,i}}{\sum_{i=1}^{k} \mathrm{P}_{buff,i}} & if \quad \sum_{i=1}^{k} \mathrm{P}_{buff,i} > 0 \\ 1 & otherwise \end{cases} \tag{3.2}$$

Given the fairness parameter for each of the users, then the scheduler calculates the weight for each user by considering their requested data rate, R_i, the size of video frame during the transmission, $S_{frame,i}$, the minimum number of video frames in the buffer, f_{min}, the number of video frames available in the buffer, f_i, and average throughput, T_i, as shown in the Equation 3.3. The scheduler will select a user with the highest weight among other users to be scheduled and assign the resources to that user. After a user has been scheduled, the system records the number of frames in the buffer to provide feedback information to the scheduler about the buffering time.

$$i^* = argmax\left\{ V_i \times \left(\frac{R_i}{S_{frame}} exp(f_{min} - f_i) + \frac{R_i}{T_i} \right) \right\} \tag{3.3}$$

QoE Model

In these paragraphs, we describe how to translate the duration of buffering times experienced by a user into the user's level of satisfaction in terms

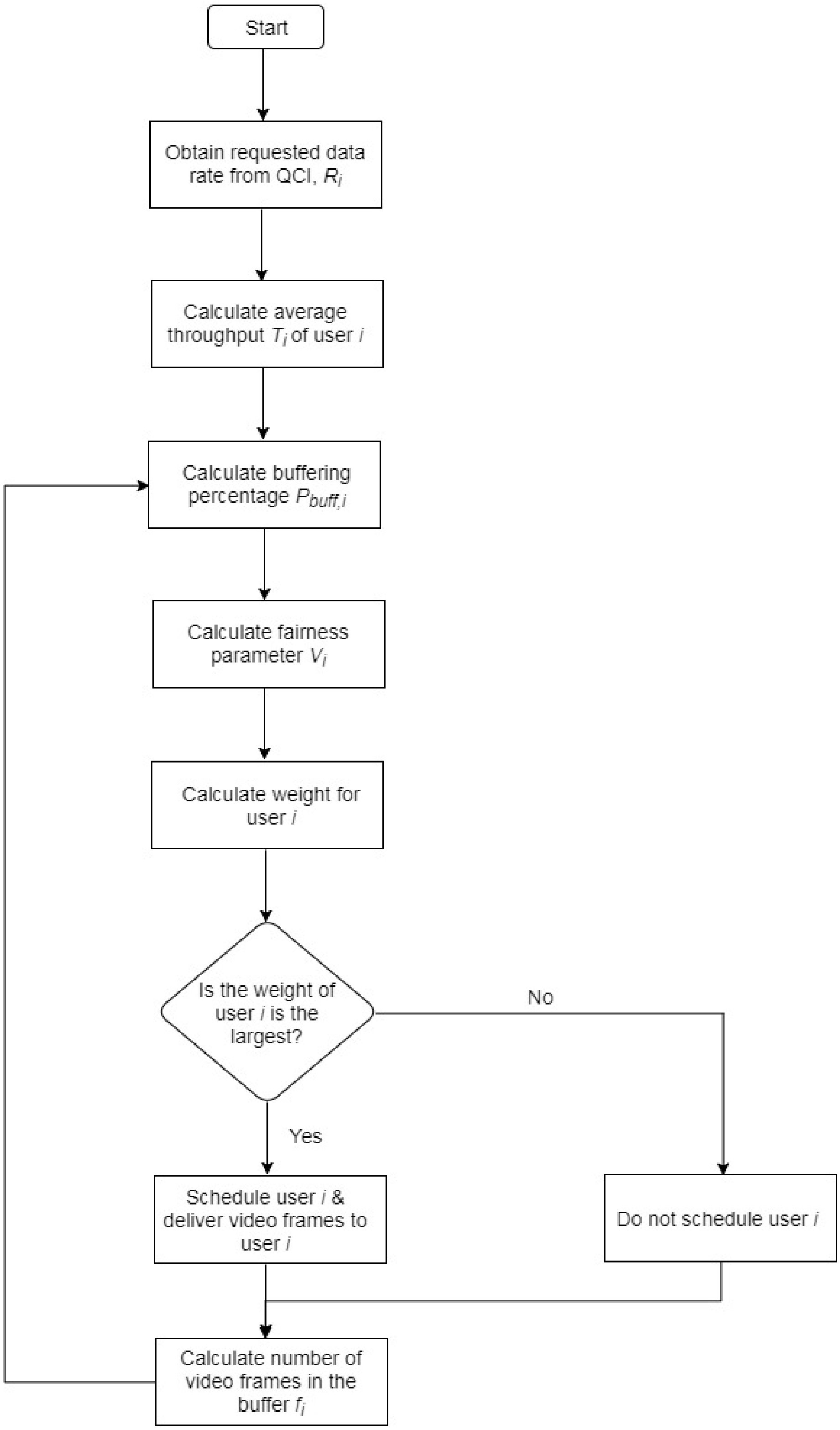


Figure 3.3 QoE-based Scheduling Algorithm

of MOS values. Numerous studies have been conducted to investigate the methods used to obtain the level of satisfaction from the user's experience. Especially in video traffic consumption, most of the studies are based on subjective tests, such as those performed by T. De Pessemier et al. [54]. They explored a threshold at which the technical quality of a mobile video service becomes unacceptable for users through subjective tests over a socio-demographic survey. Egge et al. [55] investigated the impacts of waiting time perception on QoE for web serving and video streaming traffic. The level of quality of the user's perception is collected in terms of MOS value using crowd-sourcing. Both subjective tests and crowd-sourcing consume a lot of resources and are not feasible to be executed in real time as needed in QoE-based resource allocation. Tran et al. [42] investigated the impacts of quality variations and interruptions on the QoE of a session. They tested their proposed model to gather a predicted MOS using an objective test. However, their overall proposed model considers 24 parameters and numerous measurements which lead to complexity and longer time to process.

Another objective test method to obtain the MOS value of a user's perception was proposed by Q. Huynh-Thu and M. Ghanbari [39]. The method is based on a no-reference approach to model the impact of frame freezing impairments on perceived video quality. Their proposed model was validated by subjective tests and the result showed a high correlation between subjective data and prediction data from their model. This method is applied in this research with consideration of the suitability of the user's perception metric being observed (i.e., frame freeze which represents a buffering event during video playback).

The model needs to record the buffering time events during a session of video consumption. A cumulative histogram will be used to represent the distribution of buffering time in terms of frequency and their durations. The histogram implies two important parameters: $FrDr$ and $FrTotDur$. $FrDr$ are bins that represent the duration of buffering time of an individual. $FrTotDur$ means the total duration of buffering time obtained by multiplying the frequency/number of occurrences of each bin by its associated duration. Next, the different duration values showed in each bin b are normalized to the total duration of the video, $TotDur$.

$$FDP(b) = \frac{FrDur(b)}{TotDur} \times 100 \quad (3.4)$$

$$FTDP(b) = \frac{FrTotDur(b)}{TotDur} \times 100 \quad (3.5)$$

Then the following mapping function is employed to provide good correlation with subjective data (Eq. 3.6).

$$T1(b) = \frac{1}{f2(FTDP(b)) \times f1(FDP(b)) + f3(FTDP(b))} \quad (3.6)$$

where

$$f1(x) = a1 + b1 \times log(c1 \times x + d1) \tag{3.7}$$

$$f2(x) = a2 \times x^2 + b2 \tag{3.8}$$

$$f3(x) = a3 \times x^2 + B3 \tag{3.9}$$

The constants in Equations 3.7 - 3.9 were empirically determined by Q. Huynh-Thu and M. Ghanbari using least-square regression on the subjective data: a1 = 5.767127, a2 = -0.00007, a3 = 0.000328, b2 = -0.088499, b3 = 0.637424, c1 = 3.442218, and d1 = 3.772878.

Each $T1(b)$ value is then bound in the range [1,5] as these represent the range of possible MOS scores:

$$T1'(b) = min(max(T1(b), 1), 5) \tag{3.10}$$

Then the MOS score of each user is obtained from the minimum temporal video quality:

$$T1 = min(T1'(b)) \tag{3.11}$$

Equations 3.6 until 3.10 provide a series of quality values for all bins in the histogram. In Equation 3.11, the bin that has minimum value is selected to be the one which contributes most to the degradation of the user's perception. The final output of the experimental design is the quality level of the user's satisfaction in terms of MOS values on a scale 1 to 5.

All these steps, starting from allocating resource to users until acquiring users' satisfaction level, are implemented in a Matlab based simulation tool.

3.3.3 Profitability Measurement

Given the collected data of users' satisfaction levels from the simulation, these data are analyzed from a business point of view in order to answer the research question. Statistical and mathematical calculation are used for data analysis since we want to compare quantitatively the impact of utilizing QoE-based resource scheduler and PF scheduler to profitability. Profitability relates the monetary surplus gained from a trade transaction. However, when that concept is applied in this project, there may be a problem when setting a service price based on QoE level, since the user's desire to purchase QoE-based services is out of the control of network operator, unless there is a reference data of price list based on QoE level for mobile service. The profitability that will be discussed in this project is in the context of the advantage or benefit of employing one of two compared schedulers. Furthermore, QoE is highly correlated to the satisfaction level of users and customer churn [56].

Therefore, we compare the benefits of PF and QoE-based resource scheduler by measuring the revenue loss based on churn rate.

The profitability of the two schedulers are assessed by comparing the deployment cost of implementing the schedulers and the revenue loss due to customer churn that relates to the degree of users' satisfaction.

The acceptable QoE level of service is taken to be at least fair quality, indicated with a score of MOS level 3 [57]. Here we assume that the network operator would consider users who experience a QoE level below 3 would be at risk of switching to another network operator.

According to Ericsson study about customers' loyalty [22], mobile broadband experience emerges as the principal driver of smartphone user loyalty towards operators. The study stated that 73% of global users suffer dissatisfaction due to mobile broadband experience. Furthermore, from the study, it is known that 12% of users are actively dissatisfied users, while only 5% of users explicitly state they will switch operator. From this finding, we assume that 42% of unsatisfied users who are unable to achieve a MOS level of at least 3 will likely churn from their current subscription.

The loss of revenue due to customer churn can be attained by first knowing the monthly price paid by a user. Swedish Post and Telecom Authority (PTS) stated that the monthly price of a Swedish subscription amounts to SEK 195 or €20.35 per month [58]. Then the loss of revenue due to customer churn can be calculated by considering the cost of a subscription per month multiplied by the predicted number of churned users.

The deployment cost of mobile network infrastructure is calculated according to key cost drivers for radio access network as described in the work by K. Johansson [43]. The list of cost drivers includes Capex and Opex cost. Capex includes all the expenses related to the investment in the network infrastructure, such as base station equipment, site installation, site buildout, and radio network controller equipment. Opex relates to the cost of operation and maintaining the network infrastructures, for examples electric power, operation and maintenance (O&M), and site lease.

By comparing the revenue loss of PF and QoE-based resource schedulers, as well as the deployment cost of building LTE networks, we can obtain the comparison of profitability between two schedulers to answer the research question.

3.4 Quality Assurance

Before delivering results to answer the research question, the reliability and validity of the analyzed data should be assessed. However, there may be several factors that impact the quality assurance of the results which are described in the following.

3.4.1 Reliability

Reliability means the consistency of the results for every instance of testing. Since we use an experimental method, we can control the variables involved in the simulation. To assure the reliability of these results, we only manipulate the variables that we are interested in to see their impacts in the results, while other variables remain unchanged. The variables manipulated in the simulation are the metrics involved in RRM schemes. For the PF scheduler only QoS metrics are involved, while for QoE-based resource scheduler, QoE metrics are also considered. With this experiment method, the reliability of the results can be achieved. Furthermore, to test the consistency of the results, we conducted the simulations of the two schedulers in different number of base stations in a LTE network. By doing this, we can see the trend of the results and examine its consistency.

3.4.2 Validity

Validity means how accurate the experiment measures what is intended to be measured. Since the simulation was conducted in a simplified LTE network and only considers video traffic, there may be an issue about the external validity in the context of a real network in practice. However, we compare the collected data from simulation with other work by Singh et al. [9] that used the same model, to assure the *internal* validity of the technical outcomes. The profitability is measured by considering the revenue loss calculation which based on the average price paid per month by each user according to PTS's data, hence the validity of the results could not be checked with regard to the real mobile operator's revenues.

Chapter 4

Simulation Set Up

Based on the research problem that questions the profitability of a QoE-based resource scheduler over a conventional scheduler, an experimental research method was chosen, and this selection led to the decision to use simulation to conduct experiments. The aim of simulation is to collect data that can be used to make performance comparison of the two schedulers in terms of MOS scores. This chapter explains the simulation set up to implement both the PF and QoE-based resource schedulers. Additionally, this chapter explains of characteristics of a video file, LTE system parameters, and the simulated network's dimensions.

4.1 Video Clip

In the simulation, we assume that all users are streaming the same video file. This video file, namely BigBuckBunny is taken from a public source for short movies, and the video is MPEG-4 Part 14 (.mp4) format. The initial duration of the video is 10 minutes. However, we cut the video into 70 seconds clip and it contains 1680 frames since we work in the unit of milliseconds for this project. Although details of the encoding/decoding part are out of scope in this project, it is worth knowing that the video is encoded using H.264 with frame rate of 24 frames per second. With the clip video size of 4.82 MB, the bit rate of the video is 0.573 Mbps.

4.2 Radio Environment

The performance of the two schedulers is tested in a simplified LTE network. This LTE network parameters defines its radio environment. These parameters are described in the following subsections.

4.2.1 Propagation Model

When designing a cellular network, one should consider path loss, which is the power attenuation of an electromagnetic wave as it propagates through space. Path loss is an important element of the link budget analysis of radio-based telecommunication system. There are several path loss models that can be used to calculate propagation loss as a function of the distance between User Equipment (UE) and the base station antenna, frequency, height of base station, and the type of environment, such as urban, rural, forest, sea, etc. Some of the popular propagation models are Walfish-Ikegami and Okumura-Hatta. Okumura-Hatta, the most common model, was firstly derived by Okumura from extensive measurements in urban and suburban areas. This model is still widely used by cellular operators [59]. For this reason, the Okumura-Hatta propagation model was used to calculate the link budget in this project.

For urban environments, the Okumura-Hatta model is [60]:

$$L = 69.55 + 26.16 \times log(f) - 13.82 \times log(h_B) - C_H + [44.9 - 66.5 \times log(h_B)] \times log(d)$$

where L is the path loss in the urban area, h_B is the height of base station antenna, f is the frequency of transmission, C_H is antenna correction factor which is 0 for an urban area, and d is the distance between the base station and UE.

4.2.2 LTE System Parameters

The simulation of a simplified LTE network in Matlab used the system and path loss parameters summarized in Table 4.1.

Table 4.1 LTE Simulation Parameters

Description	**Value**
System bandwidth (Mhz)	20
Carrier frequency (Mhz)	1800
eNodeB transmit power (dBm)	46
Base station height (m)	30
Gain (dB)	18
Cable loss (dB)	2
Noise floor (dBm)	−97.5
Interference margin (dB)	8

The number of cells and sectors used in the simulation differ according to the network configuration discussed in the next section. From the system parameters above, the received power in the UE can be computed using a link budget calculation as:

$$Pr = Pt + Gain - Cable\ loss - Pathloss - Interference\ margin \quad (4.1)$$

where Pr is received power, Pt is transmitted power, and Path loss is the attenuation according to Okumura-Hatta model for the urban area. Having the received power of the UE, ratio of signal to noise (SNR) can be obtained as:

$$SNR = Pr - noise\ floor \quad (4.2)$$

Then, a user's instantaneous data rate is calculated as the following:

$$datarate = bandwidth \times log_2(1 + SNR) \quad (4.3)$$

The user's data rate will be one of input parameters in the scheduling decision of both the PF and QoE-based resource allocation schemes.

4.3 Network Dimensioning

In this project, in order to compare the performance between PF and QoE-based resource scheduler, the two schedulers are simulated in seven differently dimensioned network. The network dimensions was based on a selected area of 9.25 km^2, representing Helenelund. These networks were designed to meet the coverage demand according to the different service ranges of each base station. Thus, the number of base stations will differ in each network, and there will be various numbers of users in each cell, of the 555 total users in the area of interest. In the simulation, the users are uniformly distributed in each cell. Table 4.2 shows the detailed information of each network.

To determine the network's dimensions, we consider cells with a range that varies from 2000 to 100 m, which results in different hexagonal cell sizes. The selection of cell range variations is based on the practical macro base station's service range in cellular network. To cover the Helenelund area, 9.25 km^2, the number of base stations needed is calculated, and the number of users per cell is adjusted accordingly. The capacity demand for each network for streaming the video file is obtained by considering the video's bit rate of 0.573 Mbps.

In an LTE network, the capacity provided by a cell depends on the MIMO mode, modulation type, and number of RBs available. By using MIMO 2x2, 64QAM modulation, 50 RBs available for video traffic (assuming 50% of mobile traffic is video streaming), and three sectors in each cell, in the simulation we will have a peak data rate of 75.6 Mbps offered by the system in each cell for only video traffic.

Table 4.2 Network dimensioning

Network Dimension	Cell range (km)	Site area (km^2)	Number of users per cell
1	2	10.39	555
4	1	2.59	138 – 139
8	0.7	1.27	69 – 70
12	0.55	0.78	46 – 47
57	0.25	0.16	9 – 10
185	0.139	0.05	3
356	0.1	0.02	1 – 2

4.4 Assumptions in Simulation

There are several assumptions made in the simulated environment. In the simulated LTE network, the network only considers video traffic. In terms of the radio resources, the LTE system in the simulation has 20 MHz bandwidth which means there are 100 RBs available according to the 3GPP specification. However, given that we assume that 50% of mobile traffics are for accessing video [17], there will be 50 RBs available.

In the simulation, we consider users at fixed positions as the selected area consists of a residential neighborhood. Since a user's position is static, the instantaneous data rate of a user does not change during a run of the simulation. In addition, it is assumed that the CQI of a user is fixed during each simulation. Furthermore, in the simulation environment, carrier aggregation and interference between users are not considered in this simplified LTE network.

With these assumptions, the simulation environment does not completely represent a real LTE network in practice. Nevertheless, the measurement of the QoE-based resource scheduler and PF scheduler are not affected by much as we apply the same assumptions and controlled variables for both schedulers.

Chapter 5

Results and Analysis

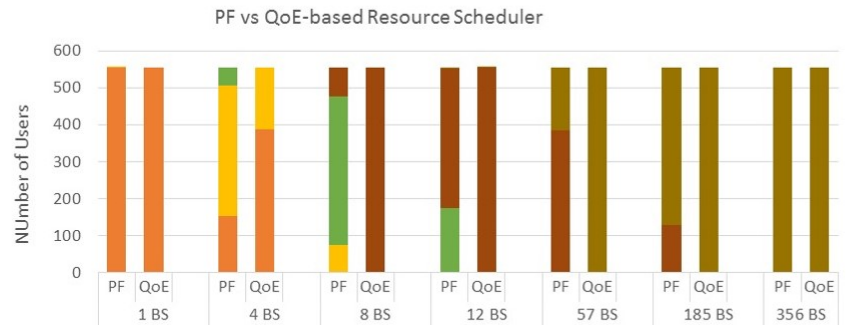
In this chapter, we discuss the solution to answer the research problem that questions the profitability of a QoE-based resource scheduler versus a conventional scheduler. The solution is based on simulations and cost analysis of the data collected from the simulation. In the simulation, we focus on comparing the performance of a QoE-based resource scheduler and PF scheduler in terms of user satisfaction level as presented in Section 5.1.1. The mean user satisfaction level, network deployment efficiency of utilizing the two schedulers, and QoE level interpretation are presented as supporting information for the performance comparison. Further, we present a cost analysis based on the simulation outcomes to compare the potential benefits between the two schedulers, with regard to the churn risk of these customers. In Section 5.2.1, the deployment cost of utilizing the two schedulers which depends on the number of base stations are depicted. Later, the revenue loss comparison of utilizing a QoE-based resource scheduler and PF are computed based on user satisfaction level in Section 5.1.1 and presented in Section 5.2.2. By considering the deviation of deployment cost and revenue loss, the profitability of the two schedulers can be measured to answer the research question, as explained in Section 5.4.

5.1 Simulation Results

In this part, the outcomes of the simulations will be presented. The purpose of the simulation is to achieve the first goal of the research, measuring the performance of PF and QoE-based resource scheduler in terms of users' QoE level. The user satisfaction level is indicated by MOS values on a scale from 1 until 5, representing bad, poor, fair, good, and excellent quality level, respectively. The data collected from the simulation is the distribution of MOS values achieved by the users for both schedulers over seven different dimensioned network. The network dimensions were based on an area of 9.25 km^2, as stated in Chapter 4.

5.1.1 User Satisfaction Level

Figure 5.1 shows the distribution of MOS values of users of the seven different network as obtained from the simulations. In this graph, Y-axis presents the number of users. On the X-axis, we can see the label of the two schedulers indicating the users' MOS values and the network's dimension. From Figure 5.1, we can see the trend of the two schedulers performance versus the overall network dimensions as well as a comparison of the performance of the two schedulers. Furthermore, we can observe the distribution of the number of users achieving a particular MOS value, shown in the table below the bar graph.



	PF (1 BS)	QoE (1 BS)	PF (4 BS)	QoE (4 BS)	PF (8 BS)	QoE (8 BS)	PF (12 BS)	QoE (12 BS)	PF (57 BS)	QoE (57 BS)	PF (185 BS)	QoE (185 BS)	PF (356 BS)	QoE (356 BS)
MOS = 5 (Excellent)	0	0	0	0	0	0	3	1	170	555	425	555	555	555
MOS = 4 (Good)	0	0	0	0	78	554	378	554	385	0	130	0	0	0
MOS = 3 (Fair)	0	0	48	0	401	1	174	0	0	0	0	0	0	0
MOS = 2 (Poor)	1	0	353	168	76	0	0	0	0	0	0	0	0	0
MOS = 1 (Bad)	554	555	154	387	0	0	0	0	0	0	0	0	0	0

Figure 5.1 MOS Scales of PF and QoE-based Resource schedulers

As shown in Figure 5.1, overall, both PF and QoE-based resource schedulers were able to offer better performance to the users as the number of base stations increases, as indicated by the improvement in the MOS scores of the users. This improvement in user satisfaction happened since with the increased number of base stations, the number of users in each cell decreases, and thus each user can be scheduled more often.

However, in the deployments with 1 and 4 base stations, the performance of a QoE-based resource scheduler was not better than a PF scheduler. In a network with one base station, all users experienced MOS scale 1, which means bad quality level, for both schedulers. When deploying 4 base stations, 387 users experienced MOS scale 1 and 168 users had MOS scale 2 by using QoE-based resource scheduler. While, by using PF scheduler, 154 users experienced MOS scale 1, 353 users had MOS scale 2, and 48 users achieved a fair quality level, MOS scale 3. Starting from a deployment of 8 base stations, the QoE-based resource scheduler performed better than the PF scheduler, and provided all users with at least fair quality, i.e., MOS scale

3. Further, the QoE-based resource scheduler was able to provide almost all users with MOS scale 4 by using 8 and 12 base stations, and MOS scale 5 with even greater numbers still varied. The users' MOS scales range from 2 to 5, with greater satisfaction as the number of base stations increases. Based on these outcomes, we can see that satisfaction level experienced by users was more uniform when using QoE-based resource scheduler

The shift in the performance of a QoE-based scheduler fits the result obtained by Singh et al.[9], where a QoE-based resource scheduler was able to achieve a lower buffering percentage compared to a PF scheduler, but PF outperformed QoE-based resource scheduler at some point where the number of users increases. This increase in the number of users can impact the fairness parameter of a QoE-based resource scheduler which depends on the number of users in each cell and users' buffering percentages, as shown in Equation 3.2. The fairness parameter causes the users of a QoE-based resource scheduler to have almost uniform QoE level and the distribution of users QoE level shifts dramatically between different dimensioned networks. While for a PF scheduler, the distribution of users' QoE level changes gradually with different numbers of base stations. The PF scheduler outperformed the QoE-based resource scheduler in terms of users' QoE level in the case of a deployment with 4 base stations.

Overall, looking at the distribution of users' QoE levels, we can state that QoE-based resource allocation is able to provide the users with a higher degree of satisfaction and at the same time assuring fairness of experience between the users as compared to a PF scheduler.

5.1.2 Mean of User Satisfaction Level

The means of MOS scores achieved by the users are shown in Figure 5.2. The horizontal axis shows seven different networks and the vertical axis shows the means of MOS values based upon total of 555 users. The means of MOS values is calculated with a 95% confidence level.

From Figure 5.2, we can see that in 1 and 4 base stations deployments, the means of MOS values of PF scheduler are higher than those when using a QoE-based resource scheduler. Further, the means of the MOS scores when using a QoE-based resource scheduler when deploying 8, 12, 57, and 185 base stations, are higher than the means of MOS scores when using PF scheduler, although deviation of means of MOS scale between different network deployments decreases as the number of base station increases.

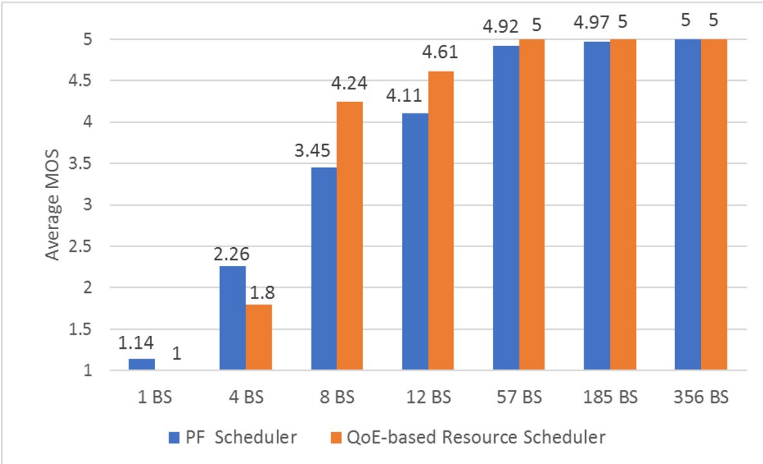


Figure 5.2 Mean of User's Satisfaction Level

The trends of users' mean QoE level for both schedulers shows improvement in the degree of user satisfaction as the number of base station increases. However, if we compare the mean of users' QoE level with the distribution of QoE levels in Figure 5.1, the mean of users QoE level shifts dramatically, especially with the increase from 4 base stations to 8 base stations, which is in line with the changes in the distribution of users QoE level over the different networks.

5.1.3 Scheduler's Impact on Network Deployment Efficiency

As mention in the previous section, MOS level 3 means fair quality. According to a study by J. Junaid, a user's experience is called acceptable if the user's MOS score is equal to or larger than 3 [57]. Based on this understanding, we set a threshold for a sufficient user experience as MOS scale 3.

Figure 5.3 illustrates the number of users achieving a MOS score above or equal to 3 for all network deployments. In one base station deployment, both schedulers were unable to give sufficient QoE level as MOS scores are around 1 and 2. If we increase to the number of base stations to 4, then a PF scheduler outperformed a QoE-based resource scheduler, but only with a slight difference, with 48 users satisfied with fair a QoE level. In a deployment of 8 base stations, the QoE-based resource scheduler was able to provide all users with at least fair QoE level, while there were 479 users achieved fair QoE level when using PF scheduler. Furthermore, we can see that starting from 12 base station deployments, PF and QoE-based resource schedulers have the same amount of users perceiving at least a fair quality MOS level.

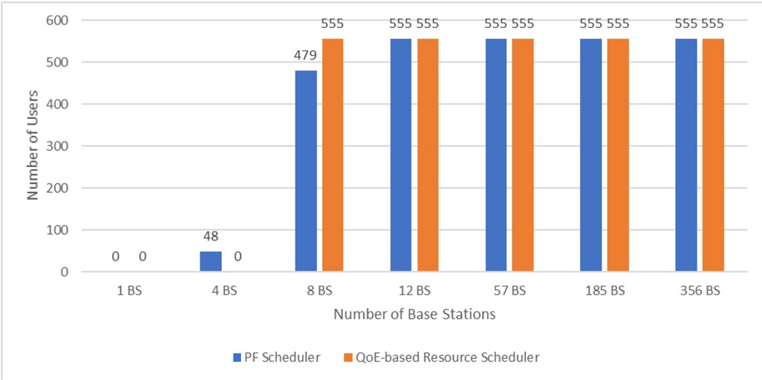


Figure 5.3 Network Efficiency with MOS $\geq$ 3

Based on these data, we can say that by utilizing a QoE-based resource scheduler, all users can be satisfied with at least acceptable quality level by only deploying 8 base stations, which means it is more efficient than using a PF scheduler which requires 12 base stations to satisfy all users.

5.1.4 QoE Level Interpretation

Users' MOS scores as the outcomes of the simulation, depends on several parameters including the duration of buffering, how many times buffering occurs (frequency of buffering), and duration of the downloaded video. By observing the simulation results, the relationship between users' MOS scores and maximum buffering percentage for a particular MOS value can be mapped, as depicted in Table 5.1. Buffering percentage in this context is described as the percentage of the duration of stalls relative to the duration of the video playout (start from users plays the video to when they finish viewing the video). It should be noted that the duration of video playout may be different between users according to the resources allocated to the users.

Table 5.1 Mapping of MOS Scales and Buffering Percentage

MOS	Buffering Percentage
1	$>$ 70%
2	50% - 70%
3	38% - 50%
4	5% - 38%
5	$<$ 5%

As we can see in Table 5.1, when a user's buffering percentage is between 50% and 70%, the user will perceive a MOS scale 2. If the user experiences buffering percentage higher than 70%, then the MOS scale will drop to 1. To achieve fair QoE level, i.e. MOS scale 3, the buffering percentage that can be tolerated is between 38% and 50% of downloaded video's duration. If the buffering percentage of a user is between 5% and 38%, the user can achieve MOS scale 4. The user's MOS level will improve to scale 5 if the buffering percentage is below 5%.

If we compare this relationship and the users' QoE level in Figure 5.1, we can see that at the point of equal performance of the two schedulers in terms of users getting MOS scale at least 3, i.e., the 12 base stations deployment, the PF scheduler utilization causes most of the users to experience a buffering percentage up to 50%. While by using QoE-based resource scheduler, the buffering percentage can be reduced to a maximum of 38%. Nevertheless, overall, for the system to be able to offer service to users with at least acceptable quality, both schedulers need to provide video streaming with maximum a 50% buffering percentage.

5.2 Cost Analysis

Given a number of users perceiving a particular QoE level as the outcome of the simulation, the collected data is analyzed from a business perspective to achieve the second goal of the research, which is to obtain the revenue loss based on the QoE level experienced by the users. This revenue loss is compared to the network deployment cost to assess the impact of these two schedulers on the mobile operator's profit. In this thesis, the cost analysis is conducted by assuming greenfield deployment, i.e., where the installation and configuration of a network does not exist. A reason to choose such a deployment is the difficulty of finding real network dimensioning since such data is generally confidential.

5.2.1 Deployment Cost

In this subsection, we assess the deployment cost of various dimensioned networks for both PF and QoE-based resource schedulers. Deployment cost consists of Capex and Opex expenditure. We calculate the Capex and Opex costs based on the key cost drivers mentioned in K. Johansson's study [43] for deploying LTE network by taking METIS data as a reference. This data included LTE equipment for a macro site, site construction, microwave link cost, the baseband unit, and software update. The METIS data containing information of price references for Capex and Opex is given in Table 5.2. Opex expenses can be derived as the percentage of the price for equipment. According to METIS data, O&M and installation are up to 15% Capex. The cost of each item will be multiplied by the number of base stations in each network, as used in the simulation.

Table 5.2 Network Deployment Cost Input

Item	Cost (K €)	Capacity
LTE Macro (1st Trx)	25	128/74 Mbps, 200 active devices (20MHz)
LTE Macro Additional Trx	15	42/25 Mbps,200 active devices (20MHz)
Site Construction Urban, Suburban(Macro)	30 to 40	
Microwave Link Cost	7	700 Mbps to 2 Gbps
O&M	represent 10%(of CapEx) and installation 5%(of CapEx)	
Baseband Unit (BBU)	6	
Software Update	100 % of BBU hardware	
Remote Radio Head (RRH)	1	

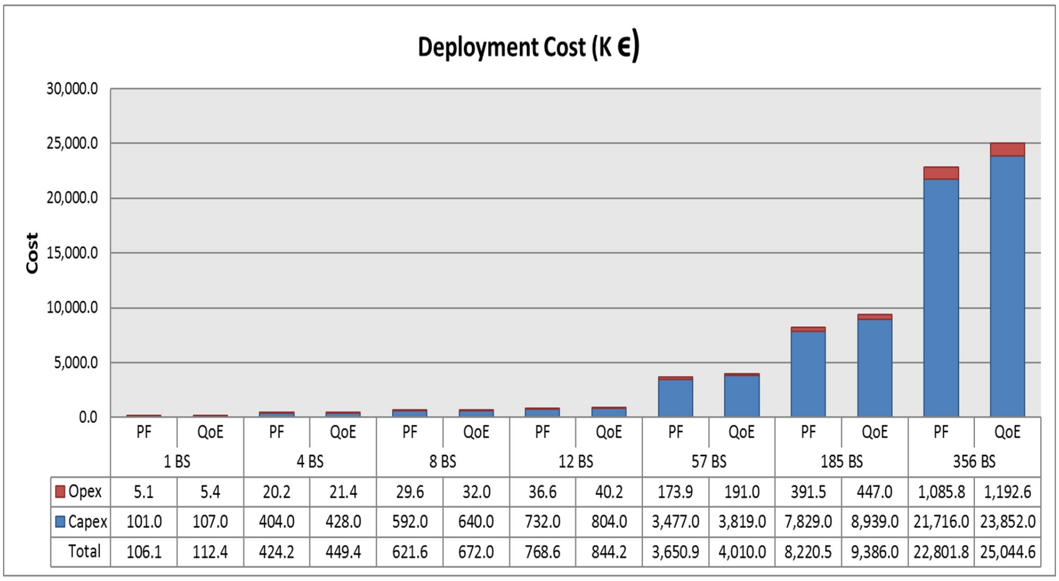
Since a PF scheduler is the most used RRM in the current LTE network [14], deployment cost for utilizing a PF scheduler in the network considers the common features in building LTE network infrastructure. As a LTE eNodeB scheduler consists of an advance software library which allows the realization of a BS scheduler function [61], the difference in deployment cost between a PF and a QoE-based resource scheduler is the software upgrade fee. For a QoE-based resource scheduler, there is an additional fee for software upgrade in Capex cost, which is 100% of baseband unit cost as mentioned in the METIS data.

Figure 5.4 shows the Capex and Opex cost of LTE network that utilize PF and QoE-based resource schedulers. The horizontal axis presents seven different networks and the two types of schedulers, while the vertical axis indicates the deployment cost in €. The total of Capex and Opex cost leads to the deployment cost for each network. As expected, as the number of base stations increases, the deployment cost also increases. That trend also applies to the difference in Capex cost between PF and QoE-based resource schedulers for the reason that the increment in Capex cost for QoE-based resource scheduler is linear with the number of base stations. It can also be noted that Capex cost dominates the deployment costs. However, the difference in Opex cost between PF and QoE-based resource schedulers is only in slight difference. At up to 12 base stations, the deployment cost is under €1K for both PF and QoE-based resource schedulers. Starting at

57 base stations, the deployment cost is €3651K and €401K and reaches €22,802K and €25,045K for 356 base stations, for PF and QoE-based resource schedulers, respectively.

If we compare the deployment cost with the user satisfaction level in Figure 5.1, we can see the cost efficiency in terms of satisfied users. For offering all users at least fair quality, MOS scale 3, the cost of deployment is €672K when utilizing a QoE-based resource scheduler in 8 base stations. That expense is lower than utilizing a PF scheduler to provide the same performance as using a PF scheduler would require 12 base stations and costs €768.6K. To satisfy all users with at least MOS scale 4, the cost of using a QoE-based resource scheduler is €844.2K (12 base stations) compared to a PF scheduler at €3651K (57 base stations). Furthermore, utilizing a QoE-based resource scheduler costs €4010K (57 base stations) to provide all users with MOS scale 5 while a PF scheduler would cost €22802K with 356 base stations in order to offer the same excellent quality to all users.

By observing the total expenses, the difference in the deployment cost between PF and QoE-based resource scheduler increases as network incorporates more base stations. The difference in cost will be compared later to revenue loss to measure the profitability of the two schedulers.



	1 BS PF	1 BS QoE	4 BS PF	4 BS QoE	8 BS PF	8 BS QoE	12 BS PF	12 BS QoE	57 BS PF	57 BS QoE	185 BS PF	185 BS QoE	356 BS PF	356 BS QoE
Opex	5.1	5.4	20.2	21.4	29.6	32.0	36.6	40.2	173.9	191.0	391.5	447.0	1,085.8	1,192.6
Capex	101.0	107.0	404.0	428.0	592.0	640.0	732.0	804.0	3,477.0	3,819.0	7,829.0	8,939.0	21,716.0	23,852.0
Total	106.1	112.4	424.2	449.4	621.6	672.0	768.6	844.2	3,650.9	4,010.0	8,220.5	9,386.0	22,801.8	25,044.6

Figure 5.4 Network Deployment Cost

5.2.2 Revenue Loss

The revenue loss is a parameter used in this thesis to compare the profitability between PF and QoE-based resource schedulers, as explained in the data analysis method in Chapter 3. The revenue loss is calculated

Table 5.3 Churn Rate of Total Users

Scheduler	**1 Base Station (%)**	**4 Base Stations (%)**	**8 Base Stations(%)**
PF Scheduler	41.98	38.38	5.77
QoE-based Scheduler	41.98	41.98	0

based on number of users that are predicted to churn due to degraded QoE level, as indicated by a low MOS scale. Since a MOS scale 3 is known to demonstrate fair QoE level, users who experience MOS scale below 3 are assumed to be a churn risk.

Table 5.3 shows the churn rate relative to the total number of users based on data collected from the simulation presented in Section 5.1.1. As we can see in Table 5.3, the churn rate only happens in the first three networks, since with networks with more than 8 base stations, the system can satisfy all users with at least fair quality level or MOS scale 3. Hence, based upon the simulations, the mobile operator does not risk customer churn when using more than 8 base stations in the network deployment.

In a one base station deployment, PF and QoE-based resource scheduler are estimated to lose 41.98% of 555 unsatisfied users, which are 233 users. By deploying 4 base stations, the churn rate of PF scheduler is 38.92% or 216 users, which is better than for QoE-based scheduler whose churn rate remains the same when using a 1 base station deployment. In contrast, with the deployment of 8 base stations, QoE-based resource scheduler does not experience risk of churn, while PF scheduler still suffers from 7.02% churn rate corresponding to 39 users.

Given a number of users that are likely to churn, the revenue loss is calculated by considering the average monthly price paid by a user. The comparison of revenue loss between PF and QoE-based resource scheduler due to customer churn is depicted in Figure 5.5 (assuming the average priced per month as given in Section 3.3.3 on page 30). It can be seen that similar to churn rate trend, in a one base station deployment, utilization of PF and QoE-based resource scheduler causes a revenue loss of €56.9K per year. By deploying 4 base stations, the revenue loss decreases to €52.01K per year for the PF scheduler. While for a QoE-based resource scheduler, the revenue loss is the same as when using one base station. The revenue loss for a PF scheduler continues to decline with a large difference until reaching €7.81K, while a QoE-based resource scheduler's revenue loss which drops to zero. With these findings, it can be said that by deploying 8 base stations, a QoE-based resource scheduler is able to avoid any customer churn due to user dissatisfaction, hence retaining current customers. However, in a number of base stations which is fewer than 8 base stations, a QoE-based resource scheduler's revenue loss is not less than a PF scheduler's. In a 4 base stations deployment, a QoE-based resource scheduler's revenue loss is slightly higher than PF scheduler's with the difference of €4.89K. In a one base station deployment, PF and QoE-based resource schedulers suffer the same amount of revenue loss because all users' QoE level are below MOS score 3 in both schedulers.

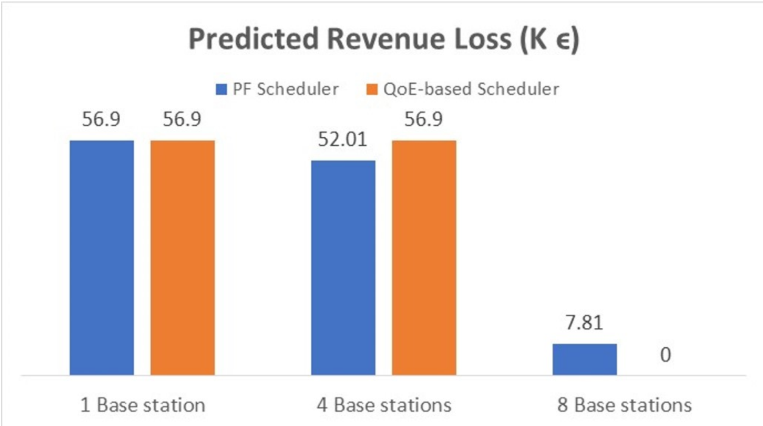


Figure 5.5 Predicted Revenue Loss due to Customer Churn

5.3 Reliability and Validity Analysis

To establish the reliability of the simulation result, we simulated the schedulers in different dimensioned network. The results of the simulations showed a similar trend with the previous study, conducted by S. Singh et al [9]. The results are also consistent over multiple simulations. Hence, it can be stated that the reliability of the simulation result is good.

However, since we simulated in simplified LTE network and not a the real video streaming environment, the validity of the results cannot be assured, especially with regard to external validity which is needed to generalize the results to put them in other context. Another reason for lack of external validity is that the quantization of satisfaction quality depends greatly on the type of service and metrics being observed.

5.4 Discussion

The data collected from the simulation shows that for networks of 8, 12, 57, 185, and 356 base stations, a QoE-based resource scheduler performed better than PF scheduler in terms of a user's QoE level, as indicated by MOS scale perceived by the users. For a network of 1 base station, a QoE-based resource scheduler performed equally with PF scheduler since the same number of users experiencing QoE level below the minimum acceptable quality. While for a network of 4 base stations, a PF scheduler performed slightly better than QoE-based resource scheduler with the difference of 48 more users getting an acceptable QoE level.

In the deployment of 1 base station, with a deployment cost of €106.1K and €112.4K when utilizing PF and QoE-based resource scheduler respectively, the revenue loss due to customer churn is predicted to be €56.9K. This revenue loss is 53.6% of the deployment cost of a PF scheduler and 50.61% of deployment cost of QoE-based resource scheduler. By deploying 4 base stations, the revenue loss is predicted to be 12.44% of a PF deployment cost. For the QoE-based scheduler, the revenue loss is the same as for a one base station deployment, but it amounts to 12.66% of 4 base station deployments cost. Based on this observation, the utilization of each of the two schedulers in the deployment of 1 and 4 base stations has a negative impact on the mobile operator's profitability due to severe revenue loss. Thus, these two networks are not recommended to be deployed.

There is no revenue loss due to customer churn when utilizing a QoE-based resource scheduler in an 8 base station deployments since all users receive at least MOS level 3, while a PF scheduler utilization has a revenue loss of as much as 1.53% of deployment cost. Starting from 12 base station deployments, both schedulers were able to prevent revenue loss as the number of base station increases.

The profitability assessment was done by making a comparison of the difference due to revenue loss and deployment cost for an upgrade to a QoE-based resource scheduler from a PF scheduler. This comparison is depicted in Table 5.4.

Table 5.4 Difference when deploying a QoE-based rather than a PF resource scheduler

Number of BS	Deployment Cost Difference (K€)	Revenue Loss Difference (K€)
1	6.3	0
4	25.2	4.89
8	50.4	−7.81
12	75.6	0
57	359.1	0
185	1165.5	0
356	2242.8	0

From Table 5.4, we can see that the deployment costs of a QoE-based resource scheduler for all network dimensions were higher than for a PF scheduler due to additional expenses for the software upgrade. For revenue loss, in 1 a base station configuration, both the PF and QoE-based resource scheduler suffered the same amount of loss, hence they showed equal performance. In a network with 4 base stations, QoE-based resource scheduler experienced revenue loss €4.89K higher than PF scheduler with 48 users achieving MOS scale 3 with the PF scheduler. In a network with 8 base stations, the difference in revenue loss from the QoE-based resource scheduler and the PF scheduler was €-7.81K, specifically the PF scheduler's revenue loss was €7.81K higher than the QoE-based resource scheduler's. Furthermore, if we look at the revenue loss in Figure 5.5, in a network with 8 base stations, the QoE-based resource scheduler avoided revenue loss since all the users were able to achieve at least MOS scale 3. Starting from 12 base stations utilization, both PF and QoE-based resource schedulers were able to provide all users with at least acceptable QoE.

However, if we compare the cost difference in the deployment of the QoE-based resource scheduler and the benefit gained from the revenue loss by using a QoE-based resource scheduler, the additional costs were significantly higher than the benefits obtained by reducing the revenue loss, except for a configuration with 4 base station in which the PF scheduler performed slightly better than a QoE-based resource scheduler. The performance of the QoE-based resource scheduler in terms of revenue loss performed equally with a PF scheduler for the most of the network configurations. The expense due to the extra cost invested by the mobile operator for a software upgrade does not bring comparable profit since the performances of PF and QoE-based resource scheduler were only slightly different in terms of churn rate. Therefore, based on this observation, it can be said that the use of a QoE-based resource scheduler does *not* bring greater profitability with respect to reduce revenue loss for the mobile operator as compared to a PF scheduler. These results were based on simulation using a QoE-based resource allocation scheme introduced by Singh et al. [9] and a QoE model proposed by Q. Huynh-Thu and M. Ghanbari [39], and the outcomes of our simulation are similar to those of prior works.

Overall, this work has brought some new insights to consider from an economic viewpoint for the mobile operator when planning to implement QoE in their network operations. The possibility of QoE to impact the economic consideration for a mobile operator depends on how the mobile operator manages and utilizes the QoE in their mobile network. The incorporation of QoE into resource allocation management does not bring any significant profitability to the mobile operator with regard to improved customer retention. The reason for this is that QoE-based resource allocation and PF performed equally well with respect to avoiding revenue loss in most network configurations. However, incorporating QoE may affect the business if the mobile operator applies differentiated charges based on user satisfaction level, specifically with regard to the efficiency of network deployment in terms of satisfying all users via excellent quality. Therefore, a framework for managing and utilizing QoE is essential for a mobile operator before any decisions regarding incorporation of QoE in their network's operation are made.

Chapter 6

Conclusion and Future Work

The main purpose of this thesis project was to assess the profitability of incorporating a QoE-based resource scheduler as the RRM scheme, with a comparison to the existing resource scheduler in an LTE network. In this chapter, the overall conclusion drawn from this work is presented. The limitation of the project and possible future work are also discussed in Section 6.2 and 6.3, respectively. Finally, some reflections about some impacts of this project are presented in Section 6.4.

6.1 Conclusion

In this thesis, we conducted a profitability assessment of deploying two different schedulers: a QoE-based resource scheduler and PF scheduler from a techno-economic perspective. The PF scheduler represents the current scheduler in an LTE network and only considers QoS metrics as input. In contrast, a QoE-based scheduler not only considers QoS metrics, but also considers buffering time as a QoE metric in its resource allocation algorithm. The evaluation focused on a streaming video service in a simplified LTE network, and the performance of both schedulers was evaluated in terms of the degree of user satisfaction. These users' satisfaction level were quantified in terms of MOS scores which were then interpreted in terms of churn risk. The two schedulers were simulated in different network configurations which had base stations with various service ranges. The networks considered in the simulations consist of 1, 4, 8, 12, 57, 185, and 356 base stations.

The results of the simulations showed that the density of users in network configurations has impact on the performance of the two considered RRM schemes. In the networks with fewer number of base stations, for example 1 and 4 base stations, most users in both schedulers were unable to achieve at least fair quality, i.e., MOS score 3. With the increase of base stations number in the network, both schedulers were able to provide users with a higher QoE level. In a network with 185 and 356 base stations, there were only up to 3 users per cell, which means that the scheduling schemes might not have much effect on the decision process of resource allocation. This causes a user could be assigned resources more frequently, and thus the user was able to achieve a higher QoE level.

A comparison of profitability by using the two schedulers was assessed based on the data collected from simulations in terms of revenue loss due to customer churn. Based on these simulation results and profitability calculations, although incorporating QoE metrics in an RRM scheme was able to improve users' satisfaction levels, the profitability of using a QoE-based resource scheduler is no higher than using a conventional scheduler. This conclusion is driven by the comparison of additional cost for upgrading the software in order to be aware of QoE metrics, with the benefit of reducing revenue loss by utilizing the QoE-based resource scheduler. The incremently deployment cost is not followed by an improvement in the QoE-based resource scheduler's performance in the terms of revenue loss. In most cases, the QoE-based resource scheduler performed equally with regard to providing users with at least an acceptable QoE level when compared to the conventional scheduler (in this case a PF scheduler).

Re-stating the research question as: *"Does QoE-based resource management offer profitability compared to a conventional (PF) approach?"*, the result of this project has answered that the incorporating of QoE into the resource allocation scheme does *not* bring more profitability when compared to the conventional (PF) resource allocation scheme. The reason for this answer to the research question is that the additional costs to deploy a QoE-based resource allocation are greater than the revenue loss reduction when compared to a PF scheduler deployment. Given this result, the project has given an idea of the effect of QoE-based resource scheduling deployment from an economic perspective, specifically on the operator's finances, which had not been investigated before. Furthermore, the work contributed knowledge to business actors, especially mobile operators, regarding elements to consider, specifically the QoE management framework when deciding to implement QoE in their network technology.

However, there is a possibility of another interpretation driven by the comparison of deployment cost and revenue loss difference, specifically in a network with 8 base stations. In this network configuration, although the increment of deployment cost to use a QoE-based resource scheduler is higher than the revenue loss reduction (i.e., there is not revenue loss for QoE-based RRM scheme in this network), a mobile operator may decide to deploy this QoE-based RRM scheme in order to improve their users' QoE level. The return of investment due to the increment of deployment cost could be earned in the following years by having zero revenue loss.

It is necessary to note that this thesis result builds upon a particular QoE-based scheduler as simulated for a video streaming application. A longer duration of video may have impact on the optimality of QoE-based resource scheduler since the decision process for assigning the resources based on the buffering percentage. Furthermore, another QoE-based scheduler and/or another service application may possibly bring a different conclusion since the degree of user satisfaction depends on the performance metrics of the application. Nevertheless, the simulation result of this thesis were in accordance with a previous study conducted by Sing et al. [9] and the result gives insight into the benefit of deploying a QoE-based resource scheduler.

In order to have result with stronger validity, the LTE network environment that was simulated in the project needs to be closer to a practical network by including other types of service instead of only a video service. Furthermore, the profitability of the two schedulers could be assessed by using other business models; for example, one in which different prices are charged for users according to the users' satisfaction level. However, this model may be sensitive to net neutrality issues.

6.2 Limitations

There are several limitations in the implementation of the results of the simulations, as described in the following:

1. The fact that the schedulers were only tested in a simplified LTE network may effect the validity of the simulation results.
2. In this project, we only considered streaming video traffic which is different from the real network's situation in practice.
3. Network dimensioning used in this project was done through theoretical assumptions which may differ from the real network conditions for such selected area.
4. The QoE-based resource scheduling simulated in the experiment was a scheduling scheme proposed by Singh et al. [9] and only focused on video traffic.

6.3 Future Work

The improvements that can be made regarding this thesis project basically focus on the research environment. In future work, it is suggested to include other types of service in the simulations, such as voice and web browsing, rather than only video traffic. The simulated LTE network can be improved to be a more realistic LTE network so that the allocation of resources could be more valid. The user's position also could be dynamic with certain velocities to presents the actual motion of the users.

Apart from the simulation, the cost analysis might be conducted using a different business model. In this thesis, we used revenue loss to measure profitability. Nevertheless, the analysis does not rule out of the possibility of using other business models.

6.4 Required Reflections

This project gives some insight from an economic perspective about the benefits in terms of revenue loss between use of a QoE-based scheduler when compared with a conventional scheduler used in current networks. The additional cost to improve the scheduler to be aware of QoS metrics could not be counter-balanced with reduced revenue loss. In most of the networks simulated in this project, both the PF and QoE-based resource scheduler showed similar performance, specifically they both were able to provide all users with at least an acceptable QoE level.

This thesis result is intended for mobile operators to provide some intuition of whether the better performance of a QoE-based resource scheduler provides greater benefits than a PF scheduler for a business point of view, especially in terms of revenue loss. This understanding suggests that careful observations should be made before implementing a new scheduler, thus avoiding unnecessary improvements in the network's infrastructure. However, the economic aspects cannot strictly support a given decision. Different decisions may be applicable due to the business focus of a particular mobile operator.

Bibliography

[1] N. Heuveldop, *Ericsson Mobility Report.* Ericsson, 2017. [Online]. Available: https://www.ericsson.com/assets/local/mobility-report/documents/2017/ericsson-mobility-report-june-2017.pdf

[2] EY, *Global Telecommunications Study: Navigating the Road to 2020.* EY White Paper, 2015.

[3] P. Maillé, M. Naldi, and B. Tuffin, "Price War with Migrating Customers," *IEEE International Symposium on Modeling, Analysis, and Simulation of Computer and Telecommunication Systems*, 2009, DOI:10.1109/MASCOT.2009.5362674.

[4] A. M. Hughes, *Churn Reduction in The Telecom Industry.* e-Dialog.com, 2008. [Online]. Available: http://www.dbmarketing.com/telecom/churnreduction.html

[5] GSM Association, *The Mobile Economy 2017.* GSMA Intelligence, 2017. [Online]. Available: https://www.gsmaintelligence.com/research/?file=9e927fd6896724e7b26f33f61db5b9d5&download

[6] E. Liotou, "QoE from a Telecom Operator's Persective," *Quality of Experience: From Assessment to Application, Report from Dagstul Seminar 15022*, vol. 5, January, 2015, DOI: 10.4230/DagRep.5.1.57. [Online]. Available: http://drops.dagstuhl.de/opus/volltexte/2015/5036/pdf/dagrep_v005_i001_p057_s15022.pdf

[7] A. E. Essaili, D. Schroeder, E. Steinbach, D. Staehle, and M. Shehada, "QoE-based Traffic and Resource Management for Adaptive HTTP Video Delivery in LTE," *IEEE Transactions on Circuits and Systems for Video Technology*, vol. 25, pp. 988–1001, June 2015, DOI:10.1109/TCSVT.2014.2367355.

[8] J. Kim, G. Caire, and A. F. Molisch, "Quality-aware Streaming and Scheduling for Device-to-Device Video Delivery," *IEEE/Association for Computing Machinery Transactions on Networking*, vol. 24, pp. 2319–2331, August 2016, DOI:10.1109/TNET.2015.2452272.

[9] S. Singh, O. Oyman, A. Papathanassiou, D. Chatterjee, and J. G. Andrews, "Video Capacity and QoE Enhancements over LTE," *IEEE International Conference on Communications*, June 2012, DOI: 10.1109/ICC.2012.6364806.

[10] International Telecommunication Union, "G.1080: Quality of Experience Requirements for IPTV Services," *ITU-T Recommendation G.1080*, December 2008. [Online]. Available: https://www.itu.int/rec/T-REC-G.1080-200812-I

[11] A. Perkis, P. Reichl, and S. Beker, "Business Perspectives on Quality of Experiences," pp. 97–108, March 2014, DOI:10.1007/978-3-319-02681-7-7.

[12] IDATE Consulting, "Business Perspectives on Quality of Experiences," November 2015. [Online]. Available: https://www.ericsson.com/assets/local/news/2015/11/mobile-operators-investments-whitepaper.pdf

[13] A. Hakansson, "Portal of Research Methods and Methodologies for Research Projects and Degree Projects," *Proceedings of the International Conference on Frontiers in Education: Computer Science and Computer Engineering FECS'13*, pp. 67–73, 2013, ISBN: 1-60132-243-7. [Online]. Available: http://kth.diva-portal.org/smash/get/diva2:677684/FULLTEXT02.pdf

[14] F. Liu, J. Riihijarvi, and M. Petrova, "Analysis of Proportional Fair Scheduling Under Bursty On-Off Traffic," *IEEE Communication Letters*, vol. 21, pp. 1175–1178, 2017, DOI:10.1109/LCOMM.2017.2657495.

[15] P. C. Loizou, "Speech Quality Assessment," *Multimedia Analysis, Processing and Communications*, vol. 346, pp. 623–654, 2011, DOI:https://doi.org/10.1007/978-3-642-19551-8_23.

[16] F. De Rango, P. Fazio, F. Scarcello, and F. Conte, "Overview on VoIP: Subjective and Objective Measurement Methods," *International Journal of Computer Science and Network Security*, vol. 6, pp. 140–153, January 2006.

[17] U. Ewaldsson, *Ericsson Mobility Report on the Pulse of Networked Society*. Ericsson, November 2016. [Online]. Available: https://www.ericsson.com/assets/local/mobility-report/documents/2016/ericsson-mobility-report-november-2016.pdf

[18] J. McCleskey, "Video Compression: MPEG-4," 1 January 2004. [Online]. Available: https://www.videomaker.com/article/f6/9867-video-compression-mpeg-4

[19] K. Brunnstrom, S. Beker, K. De Moor, A. Egger, and et al., *Qualinet White Paper on Definitions of Quality of Experience*. Qualinet White Paper on Definitions of Quality of Experience, Output from the fifth Qualinet meeting, Novi Sad, March 12, 2013, HAL ID:hal-00977812. [Online]. Available: https://hal.archives-ouvertes.fr/hal-00977812/document

[20] Cisco, "Cisco Virtual Networking Index: Global Mobile Data Traffic Forecast Update, 2016-2021 White Paper," p. 5, February 2017, Document ID: 1454457600805266. [Online]. Available: https://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/mobile-white-paper-c11-520862.html

[21] B. el-Darwiche, P. Peladeau, C. Rupp, and F. Groene, *2017 Telecommunication Trends*. Strategy &, PwC, 2017. [Online]. Available: https://www.strategyand.pwc.com/trend/2017-telecommunications-industry-trends

[22] Ericsson Consumer Lab, "Experience shapes mobile customer loyalty," *An Ericsson Consumer and Industry Insight Report*, August 2016. [Online]. Available: https://www.ericsson.com/assets/local/networked-society/consumerlab/reports/experience-shapes-loyalty.pdf

[23] K. Saleh, "Customer Acquisition versus Retention Costs - Statistics and Trends, publisher=Invesp, year=2014, url=https://www.invespcro.com/blog/customer-acquisition-retention,."

[24] M. McGovern, "Customers Want More: 5 New Expectations You Must Meet Now." [Online]. Available: http://www.customerexperienceinsight.com/customer-expectations-you-must-meet-now/

[25] Sandvine, "Video Quality of Experience: Requirements and Considerations for Meaningful Insight, An Industry White Paper," 2016. [Online]. Available: https://www.sandvine.com/downloads/general/whitepapers/video-quality-of-experience.pdf

[26] V. Ramamurthi and O. Oyman, "Video-QoE Aware Radio Resource Allocation for HTTP Adaptive Streaming," *IEEE International Conference on Communications 2014*, June 2014, DOI:10.1109/ICC.2014.6883464.

[27] International Telecommunication Union, "P.10: Vocabulary for Performance and Quality of Service," *ITU-T Recommendation P.10/G.100*, 22 November 2006. [Online]. Available: https://www.itu.int/rec/T-REC-P.10-200607-I/en

[28] L. G. Martinez Ballesteros, *Towards QoE-aware Mobile Infrastructures: QoE-based Resource Management in Mobile Networks.* Licentiate Thesis, School of Information and Communication Technology, Kungliga Tekniska Hogskolan, 2014, URN: urn:nbn:se:kth:diva-145213. [Online]. Available: https://www.diva-portal.org/smash/get/diva2:717277/FULLTEXT01.pdf

[29] International Telecommunication Union, "P.800: Methods for Subjective Determination of Transmission Quality," *ITU-T Recommendation P.800*, 1996. [Online]. Available: https://www.itu.int/rec/T-REC-P.800-199608-I/en

[30] A. Takahashi, O. Hands, and V. Barriac, *Standardization Activities in the ITU for a QoE Assessment of IPTV.* IEEE Communications Magazine, March 2008, vol. 46, DOI: 10.1109/MCOM.2008.4473087.

[31] International Telecommunication Union, "Objective Perceptual Multimedia Video Quality Measurement in The Presence of Full Reference," *ITU-T Recommendation J.247*, Aug 2008. [Online]. Available: https://www.itu.int/rec/T-REC-J.247/en

[32] S. A. Kyriazakos and G. T. Karetsos, *Practical Radio Resource Management in Wireless Systems.* Artech House, Inc., 2004, ISBN: 1-58053-632-8.

[33] A. Lemmes and G. Sunil, *Managing Churn to Maximize Profits.* Harvard Business School, September 2013, HBS Working Paper Number: 14-020. [Online]. Available: http://www.hbs.edu/faculty/Publication%20Files/14-020_3553a2f4-8c7b-44e6-9711-f75dd56f624e.pdf

[34] C. Timmerer, "Streaming 101: The Basics-Codecs, Bandwidth, Data Rate, and Resolution," February, 2009. [Online]. Available: http://streaminglearningcenter.com/articles/streaming-101-the-basics-codecs-bandwidth-data-rate-and-resolution.html

[35] 3rd Generation Partnership Project, "LTE, Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN), Overall description," *ETSI TS 136 300 V9.4.0*, July 2010. [Online]. Available: http://www.etsi.org/deliver/etsi_ts/136300_136399/136300/09.04.00_60/ts_136300v090400p.pdf

[36] G. Miao, J. Zander, K. W. Sung, and B. Slimane, *Fundamentals of Mobile Data Networks.* Cambridge University Press, March 2016, ISBN-13:978-1107143210.

[37] A. Anisimov, "How to Calculate LTE Throughput," 2011. [Online]. Available: http://anisimoff.org/eng/lte_throughput.html

[38] X. Wu, S. Tavildar, S. Shakkottai, T. Richardson, J. Li, , R. Laroia, and A. Jovicic, *FlashLinQ: A Synchronous Distributed Scheduler for Peer-to-Peer Ad Hoc Networks.* IEEE, August 2013, vol. 21, DOI: 10.1109/TNET.2013.2264633.

[39] Q. Huynh-Thu and M. Ghanbari, "No-Reference Temporal Quality Metric for Video Impaired by Frame Freezing Artefacts," *16th IEEE International Conference on Image Processing (ICIP)*, November 2009, DOI:10.1109/ICIP.2009.5413894.

[40] M. A. Usman, M. R. Usman, and S. Y. Shin, "A No Reference Method for Detection of Dropped Video Frames in Live Video Streaming," *Eighth International Conference Ubiquitous and Future Networks (ICUFN) 2016*, July 2016, DOI:10.1109/ICUFN.2016.7537155.

[41] Y. Xue, B. Erkin, and Y. Wang, "A Novel No-Reference Video Quality Metric for Evaluating Temporal Jerkiness due to Frame Freezing," *IEEE Transactation on Multimedia*, vol. 17, pp. 134–139, January 2015, DOI:10.1109/TMM.2014.2368272.

[42] H. T. T. Tran, N. P. Ngoc, A. T. Pham, and T. C. Thang, "A Multi-Factor QoE Model for Adaptive Streaming over Mobile Networks," *IEEE Globecom Workshops 2016*, December 2016, DOI:10.1109/GLOCOMW.2016.7848818.

[43] K. Johansson, *Cost Effective Deployment Strategies for Heterogeneous Wireless Networks.* Doctoral Dissertation, School of Information and Technology, Royal Institute of Technology, November 2007, ISSN: 1653–6347. [Online]. Available: http://www.diva-portal.org/smash/get/diva2:12867/FULLTEXT01.pdf

[44] J. Markendahl, *Mobile Network Operators and Cooperation: A Tele-economic Study of Infrastructure Sharing and Mobile Payment Services.* Doctoral Thesis, Department of Communication Systems, KTH Royal Institute of Technology, February 2011, ISSN:1653–6347. [Online]. Available: http://kth.diva-portal.org/smash/record.jsf?pid=diva2%3A389689&dswid=923#sthash.XuTHsYdE.dpbs

[45] 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," *IEEE Workshop on Quality of Experience-based Management for Future Internet Applications and Services*, June, 2015, DOI:10.1109/ICCW.2015.7247432.

[46] L. G. M. Ballesteros, *On the Incorporation of Quality of Experience (QoE) in Mobile Networks.* Doctoral Thesis, School of Information

and Communication Technology, KTH Royal Institute of Technology, 2017, ISBN:1978-91-7729-224-1.

[47] R. Qureshi, *Ericsson Mobility Report on the Pulse of Networked Society.* Ericsson, 2015. [Online]. Available: https://www.ericsson.com/assets/local/mobility-report/documents/2015/ericsson-mobility-report-june-2015.pdf

[48] M. Jacobson, "Helena gav Namn åt en hel Kommundel," November 2004. [Online]. Available: http://www.sollentunajournalen.se/lokalt/journalen/2004/nr5-04/helena.htm

[49] Sollentuna Municipality, "Korta fakta 2012," 2012. [Online]. Available: https://ipfs.io/ipfs/QmXoypizjW3WknFiJnKLwHCnL72vedxjQkDDP1mXWo6uco/wiki/Sollentuna_Municipality.html

[50] European Comission, "Europe's Digital Progress Report 2017," 2017. [Online]. Available: ec.europa.eu/newsroom/document.cfm?doc_id=44460

[51] R. Vannithamby and S. Talwar, *Towards 5G: Applications, Requirements and Candidate Technologies.* John Wiley and Sons, January 2017, ISBN:978-1-118-97983-9.

[52] N. Bechir, M. Nasreddine, A. Mahmoud, H. Walid, and M. Sofien, "Novel Scheduling Algorithm for 3GPP Downlink LTE Cellular Network," *Procedia Computer Science*, vol. 40, pp. 116–122, 2014, DOI:https://doi.org/10.1016/j.procs.2014.10.038. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1877050914014057

[53] J. Dahl, "The Four Elements of Video Performance," August 2016. [Online]. Available: https://mux.com/blog/the-four-elements-of-video-performance/

[54] T. De Pessemier, K. De Moor, W. Joseph, and L. De Marez, L. Martens, "Quantifying the Influence of Rebuffering Interruptions on the User's Quality of Experience during Mobile Video Watching," *IEEE Transactions on Broadcasting*, vol. 59, pp. 47–61, March 2013, DOI:10.1109/TBC.2012.2220231.

[55] S. Egge, T. Hossfeld, R. Schatz, and M. Fiedler, "Waiting Times in Quality of Experience for Web Based Services," *International Conference on Quality of Multimedia Experience 2012*, 2012, DOI:10.1109/QoMEX.2012.6263888.

[56] P. Casas, A. D'Alconzo, F. Wamser, M. Seufert, and et al, "Predicting QoE in Cellular Networks Using Machine Learning and in-Smartphone Measurements," *Ninth International Conference on Quality of Multimedia Experience*, June 2017, DOI:10.1109/QoMEX.2017.7965687.

[57] J. Junaid, *Network-based Monitoring of Quality of Experience.* Doctoral Dissertation, Department of Communication Systems, Blekinge Institute of Technology, September 2015, ISBN:978-91-7295-309-3.

[58] Swedish Post & Telecom Authority, "Summary of the PTS Price Report 2015," 2015. [Online]. Available: https://www.pts.se/upload/Documents/EN/PTS-price-report-2015-%20summary.pdf

[59] T. Schwengler, *Radio Propagation Modeling.* Chapter 3 of Class Notes for TLEN-5510-Wireless & Cellular Communication, Fall 2017, University of Colorado Boulder, Version 3.9, August, 2016. [Online]. Available: http://morse.colorado.edu/~tlen5510/text/classwebch3.html

[60] H. Holma and A. Toskala, *WCDMA for UMTS: HSPA Evolution and LTE.* John Wiley and Sons, August 2010, ISBN: 978-0-470-68646-1.

[61] IS-Wireless, "LTE eNodeB Scheduler," 2017. [Online]. Available: https://www.is-wireless.com/small-cells/lte-enb-scheduler/

TRITA-ICT-EX-2017:197