Utility-Based Resource Allocation Framework for QoE/QoS Maximization in OFDMA Networks

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Abstract. *This meta-paper describes the style to be used in articles and short papers for SBC conferences. For papers in English, you should add just an abstract while for the papers in Portuguese, we also ask for an abstract in Portuguese ("resumo"). In both cases, abstracts should not have more than 10 lines and must be in the first page of the paper.*

Resumo. *Este meta-artigo descreve o estilo a ser usado na confecção de artigos e resumos de artigos para publicação nos anais das conferências organizadas pela SBC. É solicitada a escrita de resumo e abstract apenas para os artigos escritos em português. Artigos em inglês deverão apresentar apenas abstract. Nos dois casos, o autor deve tomar cuidado para que o resumo (e o abstract) não ultrapassem 10 linhas cada, sendo que ambos devem estar na primeira página do artigo.*

1. Introduction

In recent years, it is noticeable the growing of users in cellular networks, which poses a challenge for the network operators to satisfy the Quality of Service (QoS) requirements of all these users. Radio Resource Allocation (RRA) techniques are used, for example, to provide an efficient distribution of network resources in order to improve overall system capacity. Another concept, that evaluates the users by your perception, is the Quality of Experience (QoE), where a Mean Opinion Score (MOS) is given ranging between 1 to 5 [ITU 1996]. Several algorithms based on QoE scheduling can be found in literature. The work in [Cho et al. 2015] proposed a Proportional Fair (PF) algorithm scheduler that consider the users' QoE maximization and users' fairness. In [Mushtaq et al. 2014], a downlink scheduling method is proposed, named QoE Scheme, for improving the QoE for Voice over IP (VoIP) traffic in Long Term Evolution (LTE) networks, in order to achieve higher user satisfaction. In [Liu et al. 2012], the authors proposed a QoE-based carrier scheduling scheme for multiple services that aims at maximizing the users' QoE and showed that their approach provided some improvements in terms of QoE and fairness. The work in [Toseef et al. 2011] presented a QoE-based RRA framework to be applied in heterogeneous wireless networks with different classes of services, such as VoIP, File Transfer Protocol (FTP) and video streaming.

In this work, we are interested at studying the benefits of considering both the QoS and QoE of users in resource allocation process. We propose to extend the utility-based RRA framework and algorithms (Throughput-based Satisfaction Maximization (TSM) and Delay-based Satisfaction Maximization (DSM)) presented in [Rodrigues et al. 2014] in order to consider QoE effects in system and to maximize the users' satisfaction based on their QoE metrics.

This work is organized as follows. Section 2 presents the system modeling considered in this work. In Section 3, we describe the proposed utility-based RRA framework suitable for both Non-Real Time (NRT) and Real Time (RT) services. In Section 4 we show the algorithms simulated for comparison with our proposed one. Simulation assumptions are shown in Section 4.2 and simulation results in Section 4.3, while the conclusion is drawn in Section 5.

2. System Modeling

We consider a single-cell system based on Orthogonal Frequency Division Multiple Access (OFDMA), where the set of all User Equipment (UE) is indicated by $\mathcal{J} = \{1, 2, \cdots, J\}$ and all Resource Block (RB) to be assigned to the users are organized in a set $\mathcal{K} = \{1, 2, \cdots, K\}$. We assume a downlink Single Input Single Output (SISO) channel and consider frequency-selective Rayleigh fading where each RB experiences flat fading. Furthermore, in our model, several independent snapshots with different user distributions are simulated, in order to capture the system performance in different coverage situations.

In LTE downlink networks, it is impossible for the Channel State Information (CSI) to perfectly reflect the actual channel conditions at the instant of transmission due to many real-world aspects of the system implementation. In order to model part of such imperfections, we consider that the channel information $\hat{h}_{j,k}$ sent by UE j in RB k to the Evolved Node B (eNB), $h_{j,k}$, corresponds to the real channel measure delayed by Δt Transmission Time Interval (TTI), i.e.,

$$\hat{h}_{j,k}[n] = h_{j,k}[n - \Delta t]. \tag{1}$$

Furthermore, we consider simulation scenarios comprised of one of the two following services: Constant Bit Rate (CBR), which is an NRT service; and VoIP that is a RT service. In order to investigate the performance of the studied RRA techniques over the traffic models, some metrics are implemented in the simulator. In terms of satisfaction, the algorithms are evaluated considering the percentage of satisfied users given by

$$\Upsilon[n] = \frac{J^{\text{sat}}[n]}{J}, \tag{2}$$

where $J^{\text{sat}}[n]$ is the number of satisfied users in the cell served by Base Station (BS) at TTI n, and J is the total number of users served by BS. Users are deemed satisfied if their MOS at the end of their sessions are equal or higher than a threshold $(MOS_j \geq MOS_{\text{req}})$, where the session time relies on the duration of each independent simulation. In terms of fairness, we use the Jain's fairness index, which is a measure originally proposed by [Jain et al. 1984] to evaluate how fair is the allocation of resources among users.

3. Utility-Based QoE/QoS Optimization Framework

In this section, we present the general optimization problem of the proposed framework in Section 3.1. In Section 3.2, the logistic function formulation is demonstrated. The specific formulations for NRT and RT services are shown in Sections 3.3 and 3.4, respectively. The resource allocation technique of our framework is shown in Section 3.5.

3.1. General Formulation

The considered optimization problem for NRT/RT services is the maximization of total utility with respect to the users' MOS:

$$\max_{\mathcal{K}_j} \sum_{j=1}^{J} U\left(\Phi(x_j)\right), \tag{3a}$$

$$\text{subject to} \quad \bigcup_{j=1}^{J} \mathcal{K}_j \subseteq \mathcal{K}, \tag{3b}$$

$$\mathcal{K}_i \bigcap \mathcal{K}_j = \emptyset, \quad i \neq j, \forall i, j \in \{1, 2, \ldots, J\}, \tag{3c}$$

where $U(\Phi(x_j))$ is a utility function where the input parameter is the MOS function $\Phi(x_j)$ based on a generic QoS-based variable x_j, $\mathcal{K}$ is the total number of resources in the system to be assigned to the users, $\mathcal{K}_j$ is the subset of resources assigned to user j. Constraints (3c) and (3b) state that the union of all subsets of resources assigned to different users must be limited to the total set of resources available in the system and that the same resource cannot be shared by two or more users in the same TTI, respectively.

In general, the optimum solution for the optimization problem in Equation 3 is very difficult to be obtained. A sub-optimum solution relies on splitting the problem into two stages: first, dynamic resource assignment with fixed power allocation, and second, adaptive power allocation with fixed resource assignment [Gross and Bohge 2006]. However, it has been shown for OFDMA systems that equal power allocation provides almost the same gains in comparison with adaptive power allocation with much lower complexity [Andrews et al. 2001]. Therefore, we consider the simplified optimization problem (3), which can be solved by a suitable dynamic resource assignment with equal power allocation among the resources.

In this framework we are interested in formulating techniques suitable for either NRT or RT services. Thus, we consider the variable x_j to be either throughput or end-to-end packet delay, which are QoS metrics suitable for NRT and RT services, respectively. In a generalized notation, we can simplify the objective function (3a) to become

$$\max_{\mathcal{K}_j} \sum_{j=1}^{J} U'\left(\Phi(x_j)\right) \cdot \Phi'(x_j) \cdot \mathcal{R}_j[n], \tag{4}$$

where $\mathcal{R}_j[n]$ is the instantaneous data rate of user j and $U'\left(\Phi(x_j)\right)$ is the derivative of the utility function with respect to a generic MOS function $\Phi(x_j)$ that depends on x_j, and $\Phi'(x_j)$ is the derivative of the MOS function $\Phi(x_j)$ with respect to x_j. Notice that the framework for NRT and RT services is aware of MOS functions. The problem (4) characterizes a weighted sum rate maximization, whose weights are given by

$$wQoE_j^{\text{NRT/RT}} = U'(\Phi(x_j)), \tag{5}$$

and

$$wQoS_j^{\text{NRT/RT}} = \Phi'(x_j). \tag{6}$$

On one hand, we consider that the weight given by (5) is related to QoE because the derivative is calculated with respect to a QoE metric (MOS function $\Phi(x_j)$). On the other hand, we consider that the weight given by (6) is related to QoS because the derivative is calculated with respect to a QoS metric (QoS variable x_j). These utility-based weights assume an important role in the framework proposed in the following.

3.2. Satisfaction Maximization Using the Logistic Utility Function

In [Rodrigues et al. 2014], the authors presented a sigmoid utility function based on a generic QoS metric x_j that was used in two techniques: Throughput-based Satisfaction Maximization TSM and Delay-based Satisfaction Maximization DSM. Both techniques achieve high levels of user satisfaction for NRT and RT services compared to classical algorithms in the 4th Generation (4G) systems. In order to maximize user satisfaction levels, we propose the same use of the logistic utility function based on a generic QoE metric $\Phi(x_j)$, as indicated below:

$$U\left(\Phi(x_j)\right) = \frac{1}{1 + e^{\mu(\Phi(x_j) - \Phi^{\text{req}})/\sigma}}, \tag{7}$$

where:

- μ is a constant (-1 or 1) that determines if the logistic function is increasing or decreasing, respectively;
- σ is a non-negative parameter that determines the slope of the function;
- Φ^{req} is the QoE requirement of a given service and determines the abscissa shift of the function. It can assume values in the MOS range.

The marginal utility function has a bell-shaped format and is given by

$$U'\left(\Phi\left(x_j\right)\right) = \frac{-\mu e^{\mu(\Phi(x_j[n]) - \Phi^{\text{req}})/\sigma}}{\sigma(1 + e^{\mu(\Phi(x_j[n]) - \Phi^{\text{req}})/\sigma})^2}. \tag{8}$$

Notice that the higher is the value of the parameter σ, the steeper is the sigmoid. A function of Φ^{req} was developed to obtain σ so that a desired step-shaped logistic function can be achieved, where the utility is equal to a value δ when the QoE metric achieves a proportion ρ of the QoE requirement Φ^{req}. Thus, we have

$$\sigma = \frac{\mu \cdot (\rho - 1) \cdot \Phi^{\text{req}}}{\log\left(\frac{1}{\delta} - 1\right)}. \tag{9}$$

The algorithms proposed in this work use only an increasing logistic function that is obtained when the μ parameter is set to -1 for both services, as presented in Figure 1. This is a novelty compared to the work in [Rodrigues et al. 2014], which proposes algorithms based on throughput and delay that use increasing (μ = -1) and decreasing (μ = 1) sigmoidal utility functions for NRT and RT services, respectively.

The narrow shaped utility function means that a user rapidly becomes satisfied if its QoE metric (MOS) approaches or exceeds the requirement. On the opposite, users

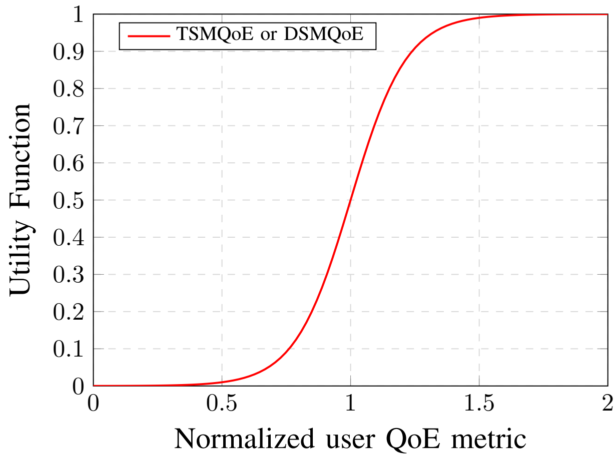

Figura 1. NRT/RT utility function

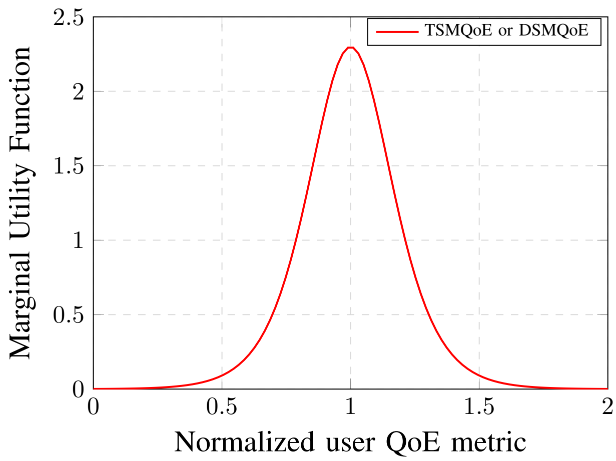

Figura 2. NRT/RT marginal utility function

become unsatisfied when their MOS is below the requirement. Satisfactory results were obtained when $\delta = 0.01$, $\rho = 0.50$ and $\Phi^{\text{req}} = 1$. For these values we obtain from Equation 9 $\sigma = 0.1088$. Figure 2 shows the bell shaped marginal utility function, which is the derivative of the sigmoidal utility function of Figure 1.

3.3. Formulation for NRT Services

3.3.1. Throughput Calculation

The NRT formulation uses as primary metric the throughput, which is calculated using a exponential filter [Antonioli et al. 2015]. As such, the throughput of user j is

$$T_j\,[n] = (1 - f_{\text{thru}}) \cdot T_j\,[n-1] + f_{\text{thru}} \cdot \mathcal{R}_j[n], \tag{10}$$

where $\mathcal{R}_j[n]$ is the instantaneous data rate of user j and f_{thru} is a filtering constant.

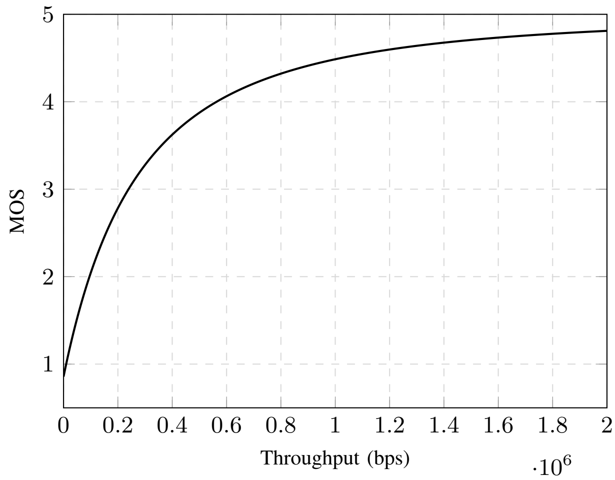

Figura 3. MOS mapping function for NRT services

3.3.2. QoE Mapping Function

Note that the original framework proposed in [Rodrigues et al. 2014] is based on QoS. In order to extend it and consider QoE, it is necessary to use a mapping function and map throughput values into opinion scores. Therefore, we use a MOS function $\Phi(T_j[n])$ described in [Poncela et al. 2014], which is shown in Equation 11 and Figure 3. The expression or the mapping function is:

$$\Phi\left(T_j[n]\right) = 5 - \frac{578}{1 + \left(\dfrac{T_j[n] + 541.1}{45.98}\right)^2}. \tag{11}$$

3.4. Formulation for RT Services

3.4.1. End-to-End Delay Estimation

In this section we show how the end-to-end delay is used in this work. As described in Section 2 we simulate the downlink of an LTE network. Thus, the end-to-end packet delay is calculated by the sum of the Head Of Line (HOL) packet delay imposed by the radio access network (d_j^{hol}) and the packet delay imposed by the Core Network (d_j^{core}):

$$d_j[n] = d_j^{\text{hol}}[n] + d_j^{\text{core}}[n]. \tag{12}$$

We use a recursive model to calculate the HOL packet delay as follows [Rodrigues et al. 2014]:

$$d_j^{\text{hol}}\left[n+1\right] = d_j^{\text{hol}}\left[n\right] + t_{\text{tti}} - \frac{1}{L} \cdot \left(\frac{\mathcal{R}_j[n] \cdot t_{\text{tti}}}{S_{\text{p}}}\right), \tag{13}$$

where t_{tti} is the duration of the TTI in seconds, L is the packet arrival rate, S_{p} is the packet size, and $\mathcal{R}_j[n]$ is the instantaneous achievable transmission rate on TTI n.

We model the core network delay d_j^{core} following a truncated Gaussian distribution with mean fixed at $105\,\text{ms}$ and using the 3σ rule to generate random values from 0 to

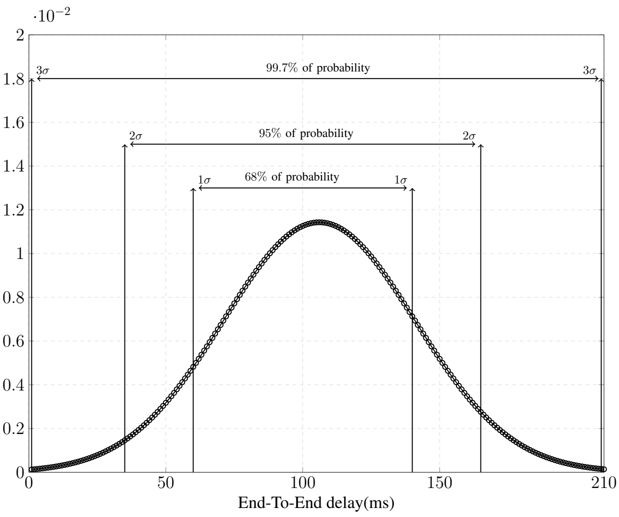

Figura 4. Core Network delay model.

210 ms, as shown in Figure 4. Thus, $d_j^{\text{core}} = \max(0; \min(0.210; d(\mu, \sigma)))$, where $d(\mu, \sigma)$ follows a Gaussian distribution with mean μ and standard deviation σ. This model aims to increase the variability in system simulations. The work in [Liu et al. 2012], which uses the same MOS and simulation scenario, consider the core network delay as a fixed value of 100 ms.

3.4.2. E-Model

The R factor is the primary output of the ITU-T E-model G.107 [ITU-T and Recommendation 2005] calculations. It is a scalar ranging between 0 and 100 that provides a prediction of the expected voice service quality which is mapped to a MOS value in our formulation. The R factor is given by

$$R = R_o - I_s - I_d - I_e + A, \tag{14}$$

where R_o is the basic signal-to-noise ratio, I_s is a combination of all impairments which occur almost simultaneously within the voice signal, I_d represents the impairments caused by delay, I_e represents the impairments caused by codecs and random packet losses, and the advantage factor A allows for a compensation of impairment factors in the modeling. According to [ITU-T and Recommendation 2005] and [Cole and Rosenbluth 2001], this value is equal to 10. For simplicity, [Cole and Rosenbluth 2001] proposes an equivalent estimation of the R factor according to the G.729a codec:

$$\begin{aligned} R\left(d_j[n]\right) \approx\ & 94.2 - 0.024 \cdot d_j[n] - 0.11 \cdot \left(d_j[n] - 177.3\right) \cdot \\ & H\left(d_j[n] - 177.3\right) - 11 - 40 \cdot \ln\left(1 + 10 \cdot \varepsilon\right) + 10. \end{aligned} \tag{15}$$

where $H(x)$ is the unit step function and ε is the network error probability. Notice that I_e in Equation 14 was estimated in [Cole and Rosenbluth 2001] under random packet loss conditions.

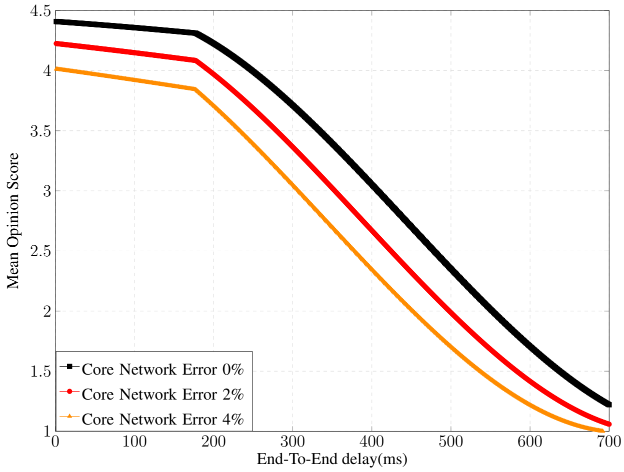

Figura 5. MOS mapping function for RT services considering different core network errors.

3.4.3. QoE Mapping Function

The MOS function $\Phi\left(R\left(d_j[n]\right)\right)$ for the voice service proposed in [Cole and Rosenbluth 2001] is illustrated in Figure 5 considering different values of the core network error and it is expressed below as:

$$\Phi\left(R\left(d_j[n]\right)\right) = 1 + 0.035 \cdot R\left(d_j[n]\right) + R\left(d_j[n]\right) \cdot \left(R\left(d_j[n]\right) - 60\right) \cdot \left(100 - R\left(d_j[n]\right)\right) \cdot 7 \cdot 10^{-6}. \quad (16)$$

3.5. Resource Allocation

This work proposes two RRA algorithms that consider both QoE and QoS. These algorithms are extensions of the TSM and DSM algorithms proposed in [Rodrigues et al. 2014], and are called TSMQoE and DSMQoE, respectively.

It is worth to mention that, apart from being formulated for an LTE network, the RRA algorithms shown in this section can be applied to any modern cellular system.

3.5.1. TSMQoE Algorithm for NRT Scenario

Since the simplified optimization problem given by Equation 4 is a weighted sum maximization problem, we can find a closed form solution for that [Song and Li 2005, Hosein 2002]. Therefore we have that the user with index $j^{\star}$ is chosen to transmit on RB k in TTI n if it satisfies the condition given by

$$\begin{aligned} j^{\star} &= \arg\max_{j} \left\{ \frac{\partial U\left(\Phi\left(T_j[n]\right)\right)}{\partial \Phi} \cdot \frac{\partial \Phi\left(T_j[n]\right)}{\partial T_j} \cdot r_{j,k}\left[n\right] \right\} \\ &= \arg\max_{j} \left\{ wQoE_j^{\text{NRT}} \cdot wQoS_j^{\text{NRT}} \cdot r_{j,k}\left[n\right] \right\}, \end{aligned} \quad (17)$$

where $r_{j,k}[n]$ denotes the instantaneous achievable transmission rate of user j with respect to RB k at TTI n, $wQoE_j^{\text{NRT}}$ and $wQoS_j^{\text{NRT}}$ are the QoE- and QoS-based weights associated to user j using an NRT service. A tiebreaker based in channel conditions is used if more than one user has the same priority. Notice that these utility-based weights play a crucial role in the resource allocation.

As commented in Section 3.2 the logistic function has its input parameter and requirement normalized by the parameter Φ^{req} that is equivalent for both QoS and QoE algorithms. However, due to this normalization, only the final weight for the TSMQoS algorithm is centered at the normalized requirement, while the combined weight for the TSMQoE algorithm has its peak below the normalized requirement because of the weights' multiplication.

3.5.2. DSMQoE Algorithm for RT Scenario

Since the simplified optimization problem given by Equation 4 is a weighted sum maximization problem, we can find a closed form solution for that [Song and Li 2005, Hosein 2002]. Therefore, we have that the user with index $j^\star$ is chosen to transmit on RB k in TTI n if it satisfies the condition given by

$$\begin{aligned} j^\star &= \arg\max_j \left\{ \frac{\partial U\left(\Phi\left(R\left(d_j[n]\right)\right)\right)}{\partial \Phi} \cdot \left| \frac{\partial \Phi\left(R\left(d_j[n]\right)\right)}{\partial d_j} \right| \cdot r_{j,k}\left[n\right] \right\} \\ &= \arg\max_j \left\{ wQoE_j^{\text{RT}} \cdot \left| wQoS_j^{\text{RT}} \right| \cdot r_{j,k}\left[n\right] \right\}. \end{aligned} \tag{18}$$

$wQoE_j^{\text{RT}}$ and $wQoS_j^{\text{RT}}$ are the QoE- and QoS-based weights associated to user j using an RT service. A tiebreaker based in channel conditions is used if more than one user has the same priority.

4. Performance Evaluation

This section presents the resource allocation algorithms taken from the literature that were evaluated and compared with the proposed RRA techniques, the simulation scenario, and the obtained simulation results. In Section 4.1, the algorithms used for comparison against our proposal are presented. The parameters adopted in our simulations are described in Section 4.2 and the obtained results are presented and discussed in Section 4.3.

4.1. State-of-The-Art Algorithms

4.1.1. NRT Scenario

Throughput-Based Satisfaction Maximization

The TSM is an RRA technique based on the Utility Theory that was proposed in [Rodrigues et al. 2014]. It uses a sigmoid function in order to maximize user satisfaction. The authors propose in [Rodrigues et al. 2014] that the user with index $j^\star$ is chosen to transmit on resource k in TTI n following the condition below:

$$j^\star = \arg\max_j \Big\{ w_j \cdot r_{j,k}[n] \Big\}, \tag{19}$$

where

$$w_j = \frac{\partial U\left(T_j[n]\right)}{\partial T_j} = \frac{-\mu e^{\mu\left(T_j[n] - T_j^{\text{req}}\right)/\sigma}}{\sigma\left(1 + e^{\mu\left(T_j[n] - T_j^{\text{req}}\right)/\sigma}\right)^2}. \tag{20}$$

that comes from a logistic bell-shaped marginal utility function.

Proportional Fairness QoE
The Proportional Fairness QoE algorithm is a version of PF with QoE properties. Note that the PFQoE algorithm proposed in [Cho et al. 2015] uses a logarithmic utility function from the generalized PF algorithm and a MOS model based on a Bezier curve. However, we simulate this algorithm with the same MOS presented in Section 3.3 in order to compare it with our proposed TSMQoE technique. A user with index $j^\star$ is chosen to transmit on resource k in TTI n following the condition below:

$$j^\star = \arg\max_j \left\{ \frac{\Phi'\left(T_j[n]\right)}{\left(\Phi\left(T_j[n]\right) - \chi\right)} \cdot r_{j,k}[n] \right\}, \tag{21}$$

where $\Phi'\left(T_j[n]\right) = \dfrac{\partial \Phi\left(T_j[n]\right)}{\partial T_j}$ is the MOS derivative with respect to throughput T_j and χ is the minimum MOS value.

4.1.2. RT Scenario

Delay-Based Satisfaction Maximization
The DSM technique was firstly proposed in [Rodrigues et al. 2014]. It uses a decreasing sigmoidal utility function, which means that the higher the HOL delay, the lower the utility derived from the network. The authors in [Rodrigues et al. 2014] showed that DSM achieved higher user satisfaction levels than other algorithms found in the literature. The resource allocation performed by this algorithm states that the chosen user should be

$$j^\star = \arg\max_j \Big\{ w_j \cdot r_{j,k}[n] \Big\}, \tag{22}$$

where

$$w_j = \frac{\partial U(d_j[n])}{\partial d_j} = \frac{-\mu e^{\mu(d_j[n] - d_j^{\text{req}})/\sigma}}{\sigma\left(1 + e^{\mu(d_j[n] - d_j^{\text{req}})/\sigma}\right)^2} \tag{23}$$

which comes from a logistic bell-shaped marginal utility function. Notice that in w_j the end-to-end delay $d_j[n]$ is considered, instead of the $d_j^{\text{hol}}[n]$ as in the original DSM technique proposed in [Rodrigues et al. 2014]. This adaptation was performed in order to compare the original DSM with the DSMQoE.

QoE Scheme
The QoE Scheme [Mushtaq et al. 2014] has a structure that maximizes user's MOS beyond a fair factor. The $j^\star$ user is chosen to transmit on resource k in TTI n if it satisfies the condition given by

$$j^\star = \arg\max_j \left\{ \Phi\left(R\left(d_j[n]\right)\right) \cdot \nu_j \cdot \left(\frac{GBR_j}{r_{j,k}[n]}\right)^\eta \right\}. \tag{24}$$

where:

- $\Phi\left(R\left(d_j[n]\right)\right)$ is the same MOS function that we use in this work;

- ν_j is a property of Proportional Fair [Kelly 1997] used for a fair resource distribution given by $\frac{r_{j,k}[n]}{T_j[n]}$;
- GBR_j is the guaranteed bit rate requirement for the VoIP user j;
- η is a tunable exponential factor for GBR VoIP traffic that can be used to increase priority of the user j in order to fulfill the GBR_j requirement.

This algorithm was chosen for comparison because it uses the users' end-to-end (as a parameter for the MOS mapping function) in order to guarantee a minimum bit rate for the users.

4.2. Simulation Parameters

Different services are employed to evaluate the performance of the algorithms for RT services or for NRT services. The CBR traffic model used in this work generates packets at 563.4 kbps (corresponding to MOS of 4), where the packet size and the inter-arrival time are fixed to 4507 bits and 8 ms, respectively. Other characteristic of this application is that delayed packets are not discarded, causing an increase in the buffer size [Nasralla and Martini 2013]. The VoIP traffic model is based on an ON/OFF Markov chain with packet size of 320 bits generated every 20 ms. Moreover, delayed packets with end-to-end delay d_j higher than 250 ms are discarded from the eNB buffer.

Furthermore, we consider imperfect CSI, where users are able to estimate their channels properly, but the eNB receives these values with delay Δt varying between 0 and 40 TTIs.

4.3. Simulation Results

In this section, we compare the performance of the proposed algorithms TSMQoE and DSMQoE with techniques presented in Section 4.1. We present the simulation results with confidence interval of 95% considering three metrics: QoE-based satisfaction, QoS-based fairness, system capacity in terms of mean cell throughput.

4.3.1. NRT Service

In Figure 6, we present the average QoE-based satisfaction by the load of users for the scenario composed of CBR users. One can see that for low user loads, the TSMQoE and TSM algorithms present performance similar to the PFQoE technique. However, when the number of users in the system increases, the performance of the PFQoE algorithm dramatically degrades, while the performance of the other algorithms slightly decreases. This is justified by the use of the logistic utility function, which is a suitable function for maximizing user satisfaction. Notice that, even though the TSM technique was not designed to deal with QoE, it achieves higher performance than the PFQoE algorithm, which was designed to this end. Furthermore, it is possible to see that the performance of the TSM and TSMQoE algorithms are very similar, with a slightly higher overall user satisfaction for the TSMQoE. This is explained by the fact that this algorithm combines two weights taking into account QoE metrics, while the TSM does not have this feature. The combination of weights employed by the TSMQoE allows users to get resource even if they are undergoing bad channel conditions, which increases the overall user satisfaction.

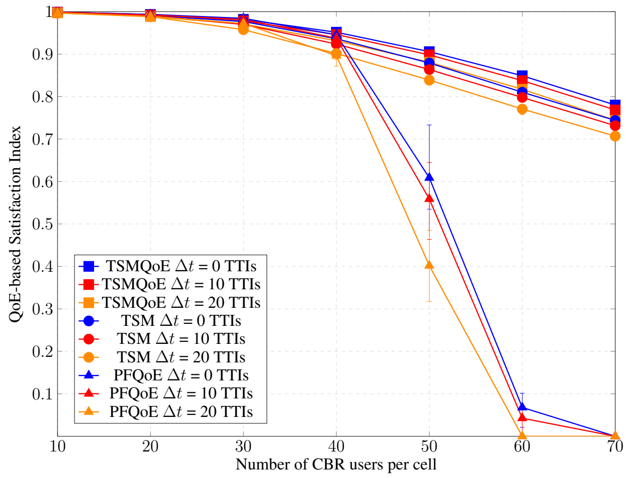

Figura 6. QoE-based satisfaction index for different algorithms with CBR service.

Concerning the CSI imperfection analysis, the performance of all algorithms decreases when Δt increases, which was expected. This performance degradation is approximately linear with the increase of Δt.

The fairness during resource allocation for different system loads and algorithms is shown in Figure 7. The PFQoE algorithm is able to keep the fairness at high values for all system loads, while the fairness index decreases when the system load increases for the TSM and TSMQoE algorithms. The reason for the is that the PFQoE algorithm was designed to guarantee such high fairness values, assuming a trade-off between high user data rates and high fairness values, which decreases its overall satisfaction index. The fairness index for the TSM and TSMQoE techniques tends to follow the trend of the satisfaction index, as it can be seen comparing figures 6 and 7. Regarding the CSI degradation, one can see that the fairness values for the PFQoE are not affected by the increase of Δt, which is expected since its objective is to keep high fairness values independently of the users' channel conditions. The fairness values for the TSM and TSMQoE decreased with the increase of Δt, as expected.

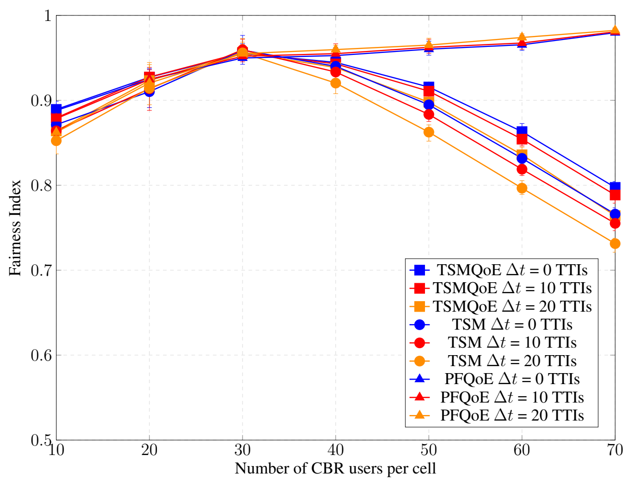

Figura 7. Fairness index for different algorithms with CBR service.

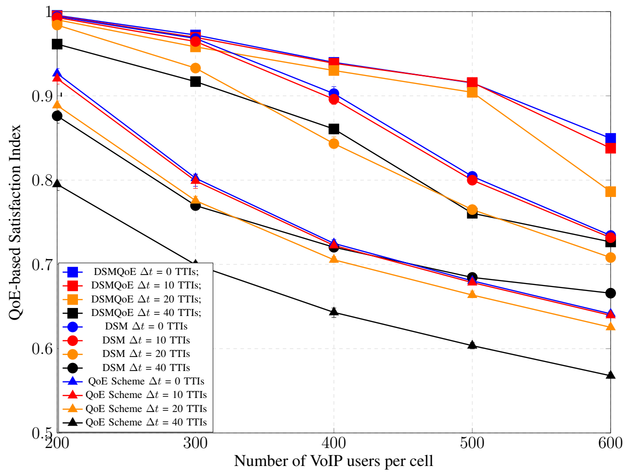

Figura 8. QoE-based satisfaction index for different algorithms with VoIP service and different CSI time delays.

4.3.2. RT Service

In this section, the performance of the proposed DSMQoE technique is compared with the DSM algorithm and a QoE-based algorithm called here QoE Scheme. Firstly, the algorithms are evaluated under distinct network errors (see Section 3), and then, the performance of algorithms are assessed assuming CSI imperfections.

CSI analysis In this section, we present the simulation results obtained when comparing our proposed algorithm DSMQoE with the DSM and QoE Scheme techniques under different measurement delays Δt. We consider for our simulations the network error ε equal to 2%.

Figure 8 presents the QoE-based satisfaction for different values of Δt for the scenario composed of VoIP users. Note that for all Δt variations, the DSMQoE algorithm outperforms the other techniques in terms of satisfaction levels because this algorithm allows users to get higher priority values even for low end-to-end delay values. This occurs due to the weights' multiplication employed by this technique. Analyzing the variations in the Δt values, one can see that the DSM technique is more sensitive to CSI imperfections, while the DSMQoE and the QoE Scheme present similar degradation under the Δt variations.

Figure 9 presents the fairness index for different system loads and values of Δt. As expected, the QoE Scheme outperforms the others algorithms and also present the lowest variation with increase of CSI measurement delay. This behavior is presented due to ν parameter in its formulation (as explained in Section 4.1) and even under high values of delays Δt, the scheduler keeps a fair resource allocation. The fairness degradation for DSM and DSMQoE is similar, but DSM outperforms DSMQoE due its smoother priority scheduling. On the other hand, the DSMQoE algorithm have an abrupt scheduling due to the MOS function, presenting the lowest fairness values.

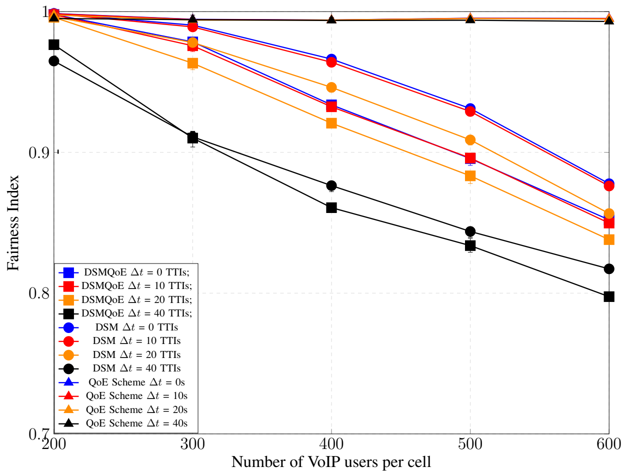

Figura 9. Fairness index for different algorithms with VoIP service and different CSI time delays.

5. Conclusion and Perspectives

The results presented in Section 4.3 confirms that our objective of proposing efficient RRA QoE algorithms, namely TSMQoE and DSMQoE, to improve user satisfaction in a scenario with either NRT or RT services was achieved. Moreover, we present a generalized utility-based QoE/QoS framework suitable for both NRT and RT services that can be used for different objectives. The reason of this characteristics is that the TSMQoE/DSMQoE techniques use a bell-shaped marginal utility combined with a MOS derivative. Notice that the operator can adopt other utility or mapping functions. From the system-level simulations results presented in Section 4.3, it can be concluded that the proposed TSMQoE and DSMQoE techniques outperform the other algorithms in terms of QoE-based satisfaction presenting also satisfactory performance in terms of fairness.

For future work, we can extend this framework to multiple services and multiple antenna schemes in order to further improve the system performance.

Referências

Andrews, M., Kumaran, K., Ramanan, K., Stolyar, A., Whiting, P., and Vijayakumar, R. (2001). Providing Quality of Service over a Shared Wireless Link. *IEEE Communications Magazine*, 32(2):150–154.

Antonioli, R. P., Rodrigues, E. B., Sousa, D. A., Maciel, T. F., and Cavalcanti, F. R. P. (2015). Adaptive utility-based resource allocation scheme for user satisfaction maximization in multi-service OFDMA systems. Technical report, GTEL-UFC-Ericsson UFC.40. Second Technical Report.

Cho, Y. H., Kim, H., Lee, S.-H., and Lee, H. S. (2015). A QoE-aware proportional fair resource allocation for multi-cell OFDMA networks. *IEEE Communications Letters*, 19(1):82–85.

Cole, R. G. and Rosenbluth, J. H. (2001). Voice over ip performance monitoring. *ACM SIGCOMM Computer Communication Review*, 31(2):9–24.

Gross, J. and Bohge, M. (2006). Dynamic Mechanisms in OFDM Wireless Systems: A Survey on Mathematical and System Engineering Contributions. Technical Report

TKN-06-001, Telecommunication Networks Group (TKN), Technical University Berlin.

Hosein, P. A. (2002). QoS control for WCDMA high speed packet data. In *Proc. 4th International Workshop on Mobile and Wireless Communications Network*, pages 169–173.

ITU (1996). Method for subjective determination of transmission quality. In *ITU-T Recommendation*, page 800.

ITU-T, R. G. and Recommendation, G. (2005). 107: The E-model, a computational model for use in transmission planning. *Recommendation ITU-T*.

Jain, R., Chiu, D., and Hawe, W. (1984). A Quantitative Measure of Fairness and Discrimination for Resource Allocation in Shared Computer Systems. Technical Report TR-301, DEC Research.

Kelly, F. (1997). Charging and rate control for elastic traffic. *European Transactions on Telecommunications*, 8:33–37.

Liu, F., Xiang, W., Zhang, Y., Zheng, K., and Zhao, H. (2012). A novel QoE-based carrier scheduling scheme in LTE-advanced networks with multi-service. In *Vehicular Technology Conference (VTC Fall), 2012 IEEE*, pages 1–5.

Mushtaq, M. S., Augustin, B., and Mellouk, A. (2014). QoE-based LTE downlink scheduler for VoIP. In *2014 IEEE Wireless Communications and Networking Conference (WCNC)*, pages 2190–2195. IEEE.

Nasralla, M. M. and Martini, M. G. (2013). A downlink scheduling approach for balancing qos in lte wireless networks. In *IEEE International Symposium on Personal Indoor and Mobile Radio Communications*, pages 1571–1575.

Poncela, J., Gomez, G., Hierrezuelo, A., Lopez-Martinez, F., and Aamir, M. (2014). Quality Assessment in 3G/4G Wireless Networks. 76(3):363–377.

Rodrigues, E. B., Lima, F. R. M., Maciel, T. F., and Cavalcanti, F. R. P. (2014). Maximization of User Satisfaction in OFDMA Systems Using Utility-Based Resource Allocation. *Wireless Communications and Mobile Computing*, pages 1–17.

Song, G. and Li, Y. G. (2005). Cross-layer optimization for OFDM wireless networks - part II: Algorithm development. *IEEE Transactions on Wireless Communications*, 4(2):625–634.

Toseef, U., Khan, M. A., Görg, C., and Timm-Giel, A. (2011). User satisfaction based resource allocation in future heterogeneous wireless networks. In *Communication Networks and Services Research Conference (CNSR), 2011 Ninth Annual*, pages 217–223. IEEE.