Adaptive Radio Resource Allocation Framework for Multi-User OFDM

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***Abstract*—Spectral efficiency, fairness and user satisfaction are crucial aspects for resource allocation in multi-user Orthogonal Frequency Division Multiplexing (OFDM)-based cellular networks. Classical Radio Resource Allocation (RRA) strategies, such as Max-Rate (MR), Proportional Fairness (PF) and Max-Min Fairness (MMF), show different performances regarding the three aforementioned aspects. In this work, we present an adaptive RRA framework that joins the criteria of the three classical strategies in a unified manner and can be dynamically configured according to the cellular operator's objectives. We exemplify the flexible use of this general framework by proposing two adaptive RRA algorithms that provide strict fairness among users and maximizes the users' satisfaction, respectively. Simulation results show that the two proposed algorithms can efficiently achieve their respective objectives by means of the adaptation of the general RRA framework.**

I. Introduction

Orthogonal Frequency Division Multiple Access (OFDMA), which is also known as multi-user OFDM, provides a high degree of flexibility that can be exploited by Radio Resource Allocation (RRA) algorithms. There are different sources of diversity in an OFDMA-based system, such as time, frequency and multi-user diversities. Consequently, it is possible to dynamically allocate subsets of sub-carriers for different Mobile Terminals (MTs), and to adapt the Modulation and Coding Scheme (MCS) and power for each sub-carrier according to the instantaneous channel conditions. In this way, opportunistic RRA algorithms can significantly improve the performance of OFDMA-based systems, achieving a higher resource utilization and system capacity.

We will primarily restrict our attention to the downlink in OFDMA-based cellular networks where there is a Base Station (BS) that allocates resources to many competing MTs. In such a scenario, spectral efficiency, fairness and user satisfaction are crucial aspects for resource allocation. The wireless shared channel is a medium over which many MTs compete for resources. From a cellular operator perspective, it is very important to use the channel efficiently because the available frequency spectrum is scarce and the revenue must be maximized. In the users' point of view, it is more important to have a fair resource allocation in a way that they are not on a starvation/outage situation and their Quality of Service (QoS) requirements are guaranteed. There are challenges in accomplishing these goals, such as the time-varying nature of the wireless environment and spatial selectivity of the sub-carriers (different MTs with different channel conditions). In general, these objectives cannot be achieved simultaneously and an efficient trade-off must be found.

Spectral efficiency is mainly characterized in terms of aggregate system throughput, which is maximized by RRA algorithms based on a ***Max-Rate (MR)*** criterion [1], [2]. This criterion gives priority to MTs with the best radio channel quality, which has the advantage of maximizing the system capacity but also has the drawback of decreasing the fairness, because MTs with poor radio propagation conditions will only be served when the remaining MTs with better channel quality have no data to transmit. On the other hand, absolute fairness can be achieved by a ***Max-Min Fairness (MMF)*** allocation [2], which has a strict fairness criterion that gives absolute priority to MTs with lower data rates. One can interpret this kind of resource allocation as an inverse form of the MR criterion, since the BS must allocate more resources to MTs with low channel quality so that they can achieve the same throughput of the others. This allocation strategy provides a fair user throughput distribution at the cost of a lower system spectral efficiency. A trade-off between spectral efficiency and fairness can be achieved by means of a ***Proportional Fairness (PF)*** resource allocation [3]. This strategy is a mix of the MR and MMF criteria that takes into account both the instantaneous achievable data rate and the average throughput that has been allocated so far to the MTs. These three RRA strategies are very suited for Non-Real Time (NRT) services, such as World Wide Web (WWW) browsing, File Transfer Protocol (FTP) and e-mail, because it is commonly accepted that the satisfaction of such service flows is measured in terms of long-term session throughput. It is important to emphasize that the above RRA strategies present different performance in terms of user satisfaction. In a general comparison, the user satisfaction in low, moderate and high system loads are higher with the MMF, PF and MR strategies, respectively.

However, all these three RRA strategies do not provide flexibility to the cellular operators. Once a given RRA strategy is statically chosen, the operator must keep with this choice during the whole operation of the network. It would be interesting to provide the cellular operators with the possibility of dynamically choosing which RRA strategy is more convenient for their interests at a given instant. In this way, different tradeoffs between spectral efficiency, fairness and user satisfaction can be fully exploited during the operation of the network.

In this work, we present an adaptive RRA framework that joins the criteria of the MMF, PF and MR strategies in a unified manner and can be dynamically configured by the BSs according to the cellular operator's objectives regarding system capacity, fairness and users' satisfaction. This generalized framework is a powerful tool that can be used in different ways. We make use of this flexibility by proposing two RRA algorithms. The first algorithm defines a fairness index for each MT based on session throughput and assures that the fairness among the MTs in a cell is kept around a planned value by means of a feedback control loop. The second one is an heuristic algorithm that dynamically adapts the proposed RRA framework in order to provide maximum user satisfaction for all ranges of system loads.

Some works in the literature tried to find an efficient trade-off between system throughput, fairness and QoS guarantees in OFDMA-based networks in a mixed traffic scenario based on cross-layer optimization [4], utility theory [5]–[8] or both of them [9], [10]. However, all the previous works perform a static resource allocation, i.e. neither the cross-layer design nor the utility functions are dynamically adapted depending on the network conditions. The novelty of our proposed RRA framework comes from the fact that it is the only one that joins in a single parametric and adaptive structure the criteria of the MR, PF and MMF, and also offers a flexible structure to be used in accordance with the network operator's objectives.

The paper is organized as follows. The system model assumed is described in section II. Section III-A presents the mathematical formulation of the classical MR, MMF and PF RRA strategies. The proposal of the adaptive RRA framework is described in section III-B, while sections III-B1 and III-B2 present two RRA algorithms that are particular uses of this general framework. The simulation results are depicted in section IV, and section V draws the conclusions of the study.

II. System Model

The system model assumed in this study considers the downlink of a single cell in an OFDMA-based wireless cellular network. The system bandwidth is divided in K sub-carriers and J MTs compete for the radio resources. Although we consider frequency-selective Rayleigh fading, each sub-carrier experiences flat fading. In this way, we assume the channel gains are constant over a Transmission Time Interval (TTI), but vary from one TTI to another.

It is also assumed that the BS has perfect knowledge of the channel gains of all MTs in all sub-carriers and that the total BS transmission power is equally divided among all sub-carriers.

Depending on channel condition, an appropriate number of bits is transmitted on each sub-carrier. Assuming discrete modulation levels $\{0, 2, 4, 6, ...\}$, the achievable transmission rate in bits/s/Hz of the kth sub-carrier assigned to the jth MT is given by:

$$c_{j,k} = 2\left\lfloor \frac{1}{2}\log_2\left(1+\frac{\gamma_{j,k}}{\Gamma}\right)\right\rfloor \tag{1}$$

where $\lfloor x \rfloor$ is an operator that returns the largest integer less than x and $\gamma_{j,k}/\Gamma$ is the effective Signal-to-Noise Ratio (SNR) of the kth sub-carrier assigned to the jth MT. The constant Γ is the SNR gap, which indicates the difference between the theoretical limit and the SNR needed to achieve a certain data transmission rate for a practical system [9]. This constant is dependent on the target Bit Error Rate (BER) and, considering an M-level Quadrature Amplitude Modulation (QAM), its value is given by $\Gamma = -\left[\ln\left(5 \cdot \mathrm{BER}\right)\right]/1.5$.

Once we have the achievable transmission rate per Hertz of each sub-carrier, the data transmission rate of each MT can be calculated. In the sub-carrier allocation process, we assume that each sub-carrier can only be assigned to one single MT. Assuming that a sub-carrier set $\mathcal{K}_j$ is assigned to the jth MT, its transmission rate is calculated as

$$r_j = \sum_{k\in\mathcal{K}_j} r_{j,k} = \sum_{k\in\mathcal{K}_j} c_{j,k}\cdot\Delta f \tag{2}$$

where $c_{j,k}$ is the channel capacity per Hertz of the kth sub-carrier assigned to the jth MT and Δf is the sub-carrier bandwidth.

A traffic model based on the WWW service is considered [11]. In the present work, we are interested at studying a worst-case scenario. Thus, we assumed the reading time of the WWW traffic model equal to zero, so that the MT would always have data in its buffer to transmit.

Finally, the resource allocation information (sub-carrier assignment, modulation and coding schemes, etc.) is sent to each MT in a separate control channel, so that the MTs can decode the data in their own sub-carriers.

III. Radio Resource Allocation Strategies

In the following, we present the formulation of the classical MR, MMF and PF RRA techniques in section III-A and describe in section III-B the proposed adaptive RRA framework that joins the criteria of the three aforementioned techniques in a single unified mathematical formulation.

A. Classical RRA Strategies

The mathematical formulations of the MR [1], MMF [2] and PF [3] are presented in equations 3, 4 and 5, respectively. The MT j^* is chosen to transmit on the kth sub-carrier in TTI n if it satisfies the condition given by the corresponding equation:

$$j^* = \arg\max_j \left\{r_{j,k}\left[n\right]\right\}, \quad \forall j \tag{3}$$

$$j^* = \arg\max_j \left\{\frac{1}{T_j\left[n-1\right]}\right\}, \quad \forall j \tag{4}$$

$$j^* = \arg\max_j \left\{\frac{r_{j,k}\left[n\right]}{T_j\left[n-1\right]}\right\}, \quad \forall j \tag{5}$$

where $r_{j,k}\left[n\right]$ is the instantaneous data rate of the jth MT on the kth sub-carrier and $T_j\left[n-1\right]$ is the average throughput of the jth MT calculated up to TTI $n-1$. The throughput of the jth MT is averaged using a Simple Exponential Smoothing (SES) filtering, as indicated in equation 6.

$$T_j\left[n\right] = \left(1 - \frac{1}{t_f}\right) \cdot T_j\left[n-1\right] + \left(\frac{1}{t_f}\right) \cdot r_j \tag{6}$$

where r_j is the instantaneous data rate (see equation 2) of the jth MT and t_f is a filtering time constant.

The MR RRA for OFDMA-based systems was firstly studied in [1]. The objective was to maximize the sum of data rates of the MTs subject to a maximum transmission power constraint. The solution is to assign each sub-carrier to the MT that has the highest channel gain on it. The MR criterion maximizes the system capacity at the cost of unfairness among the MTs, because those with poor radio link quality will probably not have chance to transmit. The MMF RRA is based on throughput and gives priority to the MT that has experienced the worst throughput so far [2]. In this way, in terms of throughput, it is the most fair criterion possible, since all MTs will have approximately the same throughput in the long-term. However, since this criterion maximizes the throughput of the worst MTs, it will provide low aggregate system throughput. One can notice that this criterion do not use instantaneous Channel State Information (CSI) of the sub-carriers. In each TTI, the chosen MT j^* will have the sub-carriers assigned to it until its buffer can be fully transmitted in that TTI. In the model assumed in this work, the MTs always have data to transmit, so the MMF RRA becomes a Time Division Multiple Access (TDMA)-like algorithm, where in each TTI all sub-carriers are assigned to the MT that satisfies equation 4. The PF RRA takes into account both the instantaneous channel conditions and the average throughput of the MTs [3]. In this way, it is a trade-off between the spectral efficiency and fairness achieved by the MR and MMF.

B. Adaptive RRA Framework

In each TTI, the BS chooses MT j^* to transmit on sub-carrier k, if it satisfies equation 7 below.

$$j^* = \arg\max_j \left\{ \frac{\left(r_{j,k}\left[n\right]\right)^{(1-\alpha)}}{\left(T_j\left[n-1\right]\right)^{\alpha}} \right\}, \quad \forall j \tag{7}$$

The parametric function of the framework can be dynamically reconfigured by adapting the parameter α, whose value determines if the proposed RRA framework adopts the MR, PF, MMF or any intermediary operation point between them. For example, if $\alpha = 0$, the priority function of the proposed RRA framework becomes the same as the MR RRA. On the other hand, if $\alpha = 1$, the proposed RRA turns out to be the MMF. The framework can also be configured as the PF if α is set to 0.5. Notice that any value between those mentioned can be chosen, which gives to the network operator a high level of flexibility to choose a desired efficient trade-off between spectral efficiency, fairness and user satisfaction.

This generalized framework can be used in many different ways, depending on the network operator's objectives. In sections III-B1 and III-B2, we present two possible RRA algorithms that adapt the parametric structure of the framework in order to achieve distinct goals: fairness guarantee and satisfaction maximization.

1) Fairness-Based RRA: The Adaptive Fairness-Based Allocation (AFA) algorithm is based on the definition of a fairness index ϕ_j, which is based on throughput and calculated for each MT in the cell. The user fairness index changes with time and is defined as:

$$\phi_j = \frac{T_j\left[n-1\right]}{T_j^{req}} \tag{8}$$

where T_j^{req} is the throughput requirement of the jth MT. Next, we define a fairness index for the whole system, which is given by equation 9 [12].

$$\Phi = \frac{\left(\sum_{j=1}^{J} \phi_j\right)^2}{J \cdot \sum_{j=1}^{J} \left(\phi_j\right)^2} \tag{9}$$

where J is the number of MTs in the cell and ϕ_j is the fairness index of the jth MT given by equation 8. Notice that $0 \leq \Phi \leq 1$. A perfect fair allocation is achieved when $\Phi = 1$, which means that the throughput allocated to all MTs are equally proportional to their throughput requirements (all user fairness indexes are equal). The worst allocation occurs when $\Phi = 1/J$, which means that all sub-carriers were allocated to only one MT.

The objective of the AFA algorithm is to assure a strict fairness distribution among the MTs, i.e. the system fairness index Φ must be kept around a planned value Φ_{target}. It is known that the fairness in the system is closely related with the RRA criterion being used. Therefore, the AFA algorithm adapts the parameter α of the general framework presented in equation 7 in order to achieve the desired operation point. In order to do that, the new value of the parameter α is calculated using a feedback control loop of the form:

$$\alpha\left[n\right] = \alpha\left[n-1\right] - \eta \cdot \left(\Phi_{filt}\left[n\right] - \Phi_{target}\right) \tag{10}$$

where $\Phi_{filt}\left[n\right]$ is a filtered version of the system fairness index using a SES filtering, Φ_{target} is the desired value for the index, and the parameter η is a step size that controls the adaptation speed of the parameter α. A SES filter, which is a first order Infinite Impulse Response (IIR) filter suitable for time series with slowly varying trends, was used to suppresses short-run fluctuations and smooth the time series $\Phi\left[n\right]$. As said before, the parameter α can vary in the range $[0, 1]$.

Looking at equation 10, one can clearly see how the parameter α is adapted over time. In each control time window, the AFA algorithm checks whether the filtered system fairness index $\Phi_{filt}\left[n\right]$ at time instant n is above or below the target value Φ_{target}. If the control error given by their difference is positive, it means that the fairness among the MTs should be decreased. In order to do that, the AFA algorithm decreases the parameter α towards its minimum value 0 by a dynamic step size that is proportional to the control error observed in that control time window. Doing that, the proposed general RRA framework works more like MR, which is characterized by low fairness and high spectral efficiency. The opposite occurs when the difference between the filtered system fairness index and its target value is negative. This indicates that the fairness among the MTs should be increased. In this way, the parameter α is increased towards its maximum value 1, and the operation point of the general RRA framework is set to be more close to MMF, which prioritizes the fairness at the cost of a low aggregate cell throughput. Since the parameter α can cover all the range $[0, 1]$, not only can the general framework be configured as MR, PF and MMF ($\alpha = \{0, 0.5, 1\}$, respectively), but it can also behave like any hybrid configuration between two consecutive classical RRA strategies, i.e. between MMF and PF or between PF and MR.

2) Satisfaction-Based RRA: The objective of the Adaptive Satisfaction-Based Allocation (ASA) algorithm is to maximize the percentage of satisfied users in the system. The motivation to propose the ASA algorithm was the fact that the classical RRA strategies present different performance results in terms of user satisfaction when the cell load varies. In general, MMF, PF and MR RRA strategies provide higher user satisfaction at low, moderate and high cell loads, respectively. This fact can be explored and the general RRA framework can be configured as any particular classical RRA strategy that provides the maximum user satisfaction in that particular time and cell load. In this way, one can make the association between the ASA and Adaptive Modulation and Coding (AMC) algorithms. The latter is a physical layer technique widely employed in wireless communication systems, which has the objective of choosing the best MCS in order to maximize the system throughput according to the instantaneous channel conditions. In a similar way, by controlling the adaptive parameter α, the ASA algorithm chooses the most appropriate classical RRA strategy in order to maximize the user satisfaction according to the instantaneous cell load and service quality conditions.

A MT is considered satisfied if its session throughput up to the present moment is higher than its throughput requirement. In each control time window, the ASA algorithm calculates the percentage of satisfied users $\Psi[n]$ and compares it to two satisfaction transition thresholds. Let us define Ψ_{MMF}^{PF} and Ψ_{PF}^{MR} as the satisfaction transition thresholds between MMF and PF, and between PF and MR, respectively. If $1 \geq \Psi[n] > \Psi_{MMF}^{PF}$, the ASA algorithm sets the α parameter to 1 and configures the proposed general RRA framework to work like the MMF. If $\Psi_{MMF}^{PF} \geq \Psi[n] > \Psi_{PF}^{MR}$, the adaptive RRA framework takes the form of PF by setting $\alpha = 0.5$. Otherwise, if $\Psi_{PF}^{MR} \geq \Psi[n] \geq 0$, the ASA algorithm sets $\alpha = 0$ and the MR criterion takes place. In this way, it is expected that the adaptation of the general RRA framework by means of the ASA algorithm will take advantage of the best that the classical RRA strategies can offer in terms of user satisfaction for different cell loads. In a real network, the values of the transition parameters Ψ_{MMF}^{PF} and Ψ_{PF}^{MR} must be chosen empirically by the cellular operator based on the observation of the network performance.

TABLE I
SIMULATION PARAMETERS

Parameter	Value	Unit
Number of cells	1	-
Maximum BS transmission power	20	W
Cell radius	500	m
MT speed	static	-
Number of sub-carriers	192	-
Sub-carrier bandwidth	15	kHz
Path loss	$128 + 37.6 \cdot log_{10}(d)$	dB
Log normal shadowing standard dev.	8	dB
Small-scale fading	Typical Urban (TU)	-
Noise power per sub-carrier	-123.24	dBm
BER requirement	10^{-6}	-
Modulation schemes	QPSK, 16-QAM, 64-QAM	-
Transmission Time Interval (TTI)	0.5	ms
Traffic model	WWW full buffer	-
Throughput filtering time constant (t_f)	50	-
User throughput requirement (T_j^{req})	1.4	Mbps
Minimum α value	0	-
Maximum α value	1	-
AFA control time window	0.5	ms
AFA target fairness index (Φ_{target})	0.9	-
AFA step size (η)	0.1	-
AFA filtering time constant	10	-
ASA control time window	100	ms
ASA transition threshold (Ψ_{MMF}^{PF})	0.95	-
ASA transition threshold (Ψ_{PF}^{MR})	0.65	-
Simulation time span	30	s
Number of realizations for each point	10	-

IV. Simulation Results

The main simulation parameters are presented in table I. The simulation results for the AFA and ASA algorithms are depicted in sections IV-A and IV-B, respectively.

A. Fairness-Based RRA

Figure 1 shows the system fairness index calculated by equation 9 for different number of users. The performance of the AFA algorithm is compared to the three classical RRA strategies: MMF, PF and MR. In this simulation scenario, the target fairness index is 0.9. It can be observed that AFA is successful to achieve its main objective, which is to guarantee a strict fairness distribution among the MTs. This is achieved due to the feedback control loop that dynamically adapts the parameter α of the general RRA framework. As expected, MMF provided the highest fairness, very close to the maximum value of 1, while MR proved to be the most unfair strategy with a high variance on the fairness distribution for high cell loads. PF presented a good fairness distribution, close to the performance of MMF. The advantage of the AFA algorithm is that it can be designed to provide any required fairness distribution, while the classical RRA strategies are static and do not have the freedom to adapt themselves and guarantee a specific performance result.

The total cell throughput for different cell loads is shown in Figure 2. As expected, MR was able to maximize the spectral efficiency, while MMF presented the lowest cell throughput. Since PF is a trade-off between MR and MMF, its performance lied between them. Looking at Figure 1, one can notice that

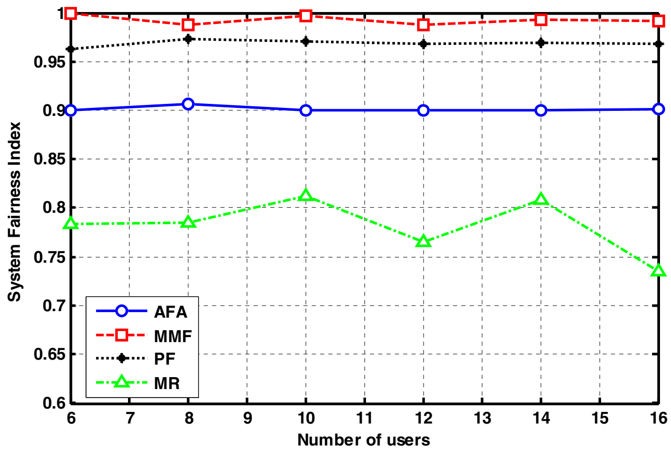

Fig. 1. Comparison of the AFA and the classical RRA strategies regarding the system fairness index

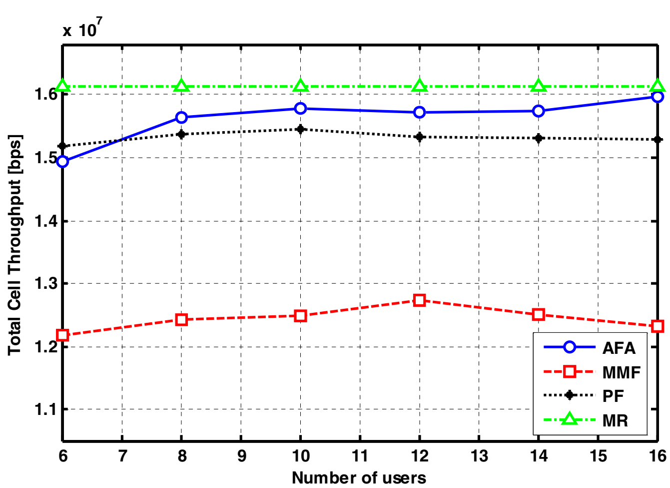

Fig. 2. Comparison of the AFA and the classical RRA strategies regarding the total cell throughput

the target fairness index equal to 0.9 forced the AFA algorithm to behave like an hybrid between the PF and MR strategies. This fact is confirmed in Figure 2, where the performance of the AFA algorithm in terms of total cell throughput turned out to be between the performances of PF and MR.

This hybrid behavior between PF and MR presented by the AFA algorithm can also be seen in the user satisfaction, as Figure 3 shows. For low and high cell loads, the performance of the AFA algorithm lies between PF and MR. However, for moderate loads, AFA provided higher percentage of satisfied users than the classical RRA strategies.

B. Satisfaction-Based RRA

Figure 4 presents the main result for the ASA algorithm: the percentage of satisfied users. Looking at the performance of the classical RRA algorithms, one can see that there are ranges of cell load in which each of the classical algorithms presents the highest user satisfaction. The ASA algorithm, by means of the adaptation of the parameter α of the proposed RRA framework, is able to select the most appropriate RRA strategy for all ranges of cell loads, i.e. the one which provides the maximum user satisfaction.

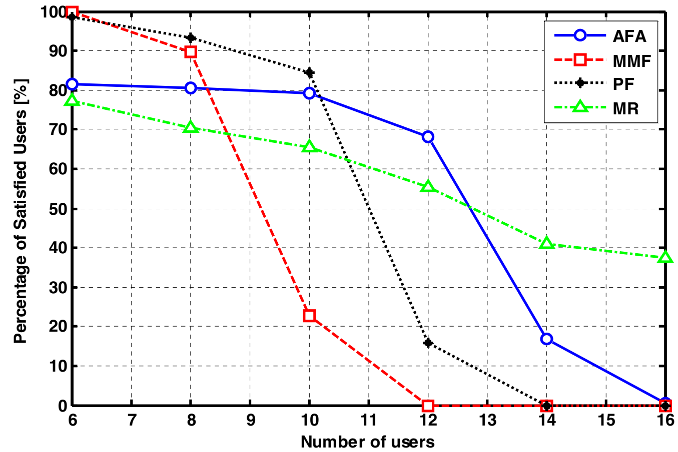

Fig. 3. Comparison of the AFA and the classical RRA strategies regarding the user satisfaction

The comparison of the ASA and the classical RRA strategies regarding the total cell throughput is presented in figure 5. It can be seen that, as the cell load increases, the cell throughput of the ASA algorithm also increases. This indicates that for low cell loads, the adaptive RRA framework was configured as the MMF strategy, for moderate loads the PF strategy was used, and finally for high loads, the framework adopted the form of MR.

This adaptation can also be observed in Figure 6, where the system fairness index is presented. Again, one can clearly notice the adaptation pattern of the proposed RRA framework by the ASA algorithm. For low cell loads, since the framework behaves like the MMF strategy, the maximum fairness alloca-

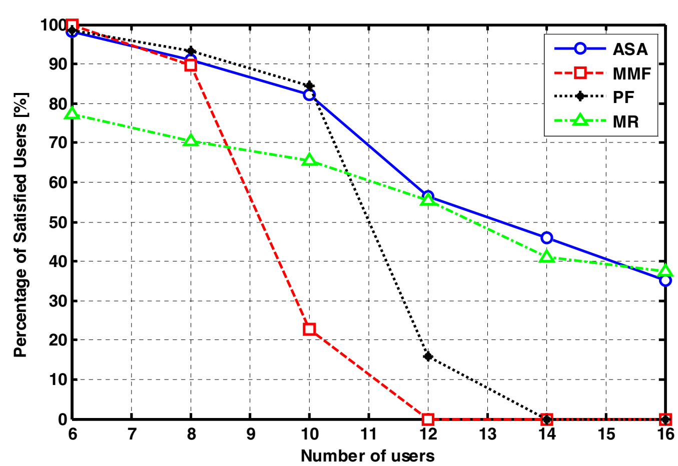

Fig. 4. Comparison of the ASA and the classical RRA strategies regarding the user satisfaction

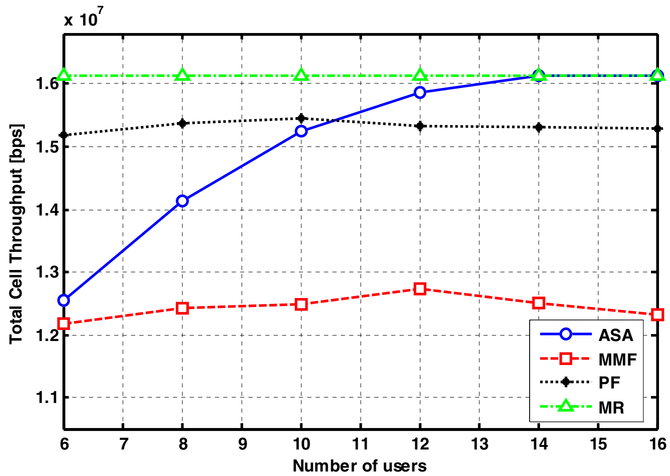

Fig. 5. Comparison of the ASA and the classical RRA strategies regarding the total cell throughput.

tion is achieved. When the load increases, the RRA framework is switched to the PF criterion, which causes a decrease in the fairness index. Finally, in order to achieve a maximum user satisfaction at high loads, the RRA framework is configured as the MR strategy, which makes the system operates with the most unfair resource allocation.

V. Conclusion

In this work, an adaptive RRA framework for OFDMA-based cellular systems is proposed. This framework has a general parametric structure that joins in a unified manner the classical RRA strategies Max-Min Fairness (MMF), Proportional Fairness (PF) and Max-Rate (MR) and provides to the cellular operators the possibility to achieve an efficient trade-off between spectral efficiency, fairness and user satisfaction. We also propose two RRA algorithms (AFA and ASA) that can use the general framework and achieve two possibles objectives of a cellular operator: strict fairness guarantee among users or maximization of user satisfaction.

The simulation results showed that the AFA algorithm was able to keep the system fairness index around a planned value of 0.9 and the ASA algorithm succeeded at maximizing the user satisfaction for all range of cell loads.

As perspectives of this study, we intend to extend the concept of the proposed RRA framework and algorithms to cope with both real-time and non real-time services, and evaluate their performance with more realistic traffic models.

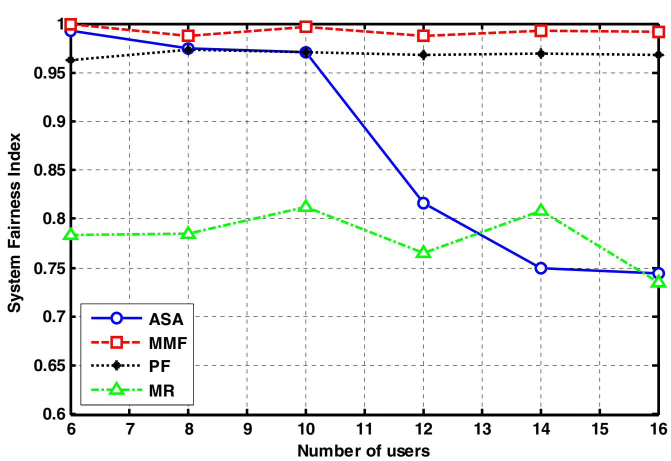

Fig. 6. Comparison of the ASA and the classical RRA strategies regarding the system fairness index

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