PHY- and MAC-aware Resource Allocation and Packet Scheduling for Single-Cell OFDMA Packet Networks

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Abstract—Radio resource management mechanisms such as PHY-centric Radio Resource Allocation and MAC-centric Packet Scheduling are expected to play a substantial role in the performance of future OFDMA-based wireless networks. Inevitably, efficient resource allocation strategies have to exploit information laying in different OSI layers, allowing for a cross-layer design. In the literature adaptive allocation schemes have been proposed for optimum or suboptimum resource distribution in the frequency domain under static individual user rate constraints. The contribution of this work is twofold: First, we evaluate current allocation schemes under realistic traffic and channel conditions, in order to acquire the upper performance bounds on a real time evolving network. Then we extend them to incorporate MAC-layer information, as well as opportunistic packet scheduling in the time-domain. The key factors that affect the overall system performance in terms of system average throughput and delay are identified, evaluated and discussed. The presented ideas are accompanied with extensive system level Monte-Carlo simulations.

Index Terms—OFDMA, Resource Allocation, Packet scheduling, multiuser OFDM, cross-layer

I. Introduction

Orthogonal Frequency Division Multiple Access (OFDMA) has been proposed as the most important Radio Access Technology, for the evolvement of current wireless cellular systems towards high speed wireless broadband networking [1]–[3]. Viewed from the physical layer perspective, OFDM is a transmission technique that allows for efficient and reliable data transmission over wideband channels [4], whereas from the MAC layer perspective it favors the flexible allocation of system resources in a multi-user scenario [5], [6]. Inevitably, efficient transmission of multimedia traffic with QoS support over OFDMA requires sophisticated strategies for Radio Resource Allocation (RRA). OFDMA–RRA algorithms are devised to dynamically distribute the available radio resources among users, while maintaining high system utilization under certain QoS constraints. These algorithms need to take into consideration both the OFDM physical layer (PHY) properties as well as the MAC layer information especially that related to the obtained QoS during the dynamic evolvement of the system.

Efficient RRA mechanisms for a multi-user OFDM system need to exploit both the inherent frequency selectivity of the wireless medium [7] and the multi-user diversity [8] allowing for optimum resource (power and subcarriers) distribution in the frequency domain, while satisfying PHY-related QoS parameters such as BER/FER and transmission data rate. Related studies so far, have treated the OFDMA–RRA problem as an optimization problem and various algorithms – optimum and suboptimum – have been developed to that purpose [9]-[18]. Additionally, in an OFDM transmission scheme the whole system bandwidth is dynamically shared among the served users in a very short time scale, equivalent to the duration of one or several OFDM symbols. As a result, Packet Scheduling (PS) algorithms become particularly important deserving special attention. Hence, the scope of PS in the context of OFDM is twofold: guarantee MAC-centric QoS and efficient OFDM resources utilization. To achieve the first goal OFDMA-PS needs to consider features obtained from traditional scheduling disciplines, like efficient data queuing, user prioritization and effective multiplexing in the time domain [19], [20]. To achieve the second goal PS has to rely on computationally efficient OFDMA–RRA algorithms.

The interplay between packet scheduling and resource allocation is a key feature for future OFDMA-based data networks. In a traditional network, these two entities lie on different OSI layers and are well defined. Regarding a multi-carrier network, joint consideration of these mechanisms is highly needed since independent optimization of any of the above entities could lead to a suboptimum overall system performance. In [21], the authors proposed a scheme based on a well known packet scheduling strategy, called GPS, in order to ensure a fair resource allocation among different users. The main drawback of this approach was the fixed bit loading per OFDM subcarrier assumption, which may constrain the achievable spectral efficiency. Another approach could be found in [22], where the authors decoupled the operation of PS and RRA entities. Despite the flexibility of this aspect, the development of an accurate interface between these two modules is of utmost importance, since the authors propose a rather simplified model. Moreover the performance of the specific approach for real-time multimedia services is not examined. Finally in [23] the joint consideration of PS and RRA based on a utility-based optimization framework is examined. Both data and real-time traffic scenarios are considered and several allocation algorithms are devised. Although this approach provides us with the optimum system performance bounds, its dependence on the choice of the adequate utility function, which is a highly subjective issue reduces its usefulness.

In our paper we first study the MAC-layer performance of the most representative OFDMA-RRA algorithms that appear in the bibliography. We observe that the PHY-centric performance is actually the upper bound of the MAC-centric performance, since in a dynamically evolving network these algorithms often fail. Based on this observation we propose several modifications of the original "PHY-centric only" approach that could render the application of these RRA algorithms in such networks under diverse data traffic services. This work is an extension of [24]; a thorough study of the actual gain acquired from implementing channel-aware RRA compared to static MAC-only RRA and the evaluation of the effect of system loading, BS power availability and Packet Scheduling strategy utilized, to the overall system performance are the main additions to the original publication.

The rest of the paper is organized as follows. Section II gives a description of the adopted system model and the respective assumptions. In Section III we first present a mathematical formulation for the static OFDMA–RRA problem, then describe and evaluate through extensive simulations various algorithms and scenarios, and finally we introduce the strategy that best fits to the scope of this work. In Section IV Packet Scheduling in the context of OFDMA is examined, and our approach for dealing with variable bit rate traffic is thoroughly presented along with representative simulation results. Conclusions and future work issues are stated in Section V.

II. SYSTEM MODEL

The downlink of an OFDMA–based single-cell wireless network is studied in the context of this work, although we could extend our findings to the uplink case as well applying minor modifications. The Base Station (BS) is located in the center of a circular area representing the cell. Mobile terminals are uniformly distributed in the same area and require a specific service type. Each user's channel comprises a large–scale and a small–scale term: the former represents path loss and shadowing and vary according to [7] while the later represents small–scale fading [25]. The fading profiles are independent among users, time-uncorrelated (Doppler Effect is not considered) and frequency-correlated for each user according to a common determined Path Delay Profile. We assume that the channel coherence bandwidth is larger than the subcarrier bandwidth and a large enough cyclic prefix is added at the end of each OFDM symbol, thus a simplified baseband channel model can be used to model the channel effect on a symbol by symbol basis (see for example [17] for the detailed derivation of this channel model). In essence the frequency-selective channel is replaced by a set of n parallel flat-fading channels [26]; each tone is described by a complex frequency response factor H_n which constitutes the channel state information (CSI). Assuming perfect CSI knowledge at the receiver the phase part of the channel can be ignored and H_n is replaced by its magnitude $|H_n|$ (usually called subcarrier gain). This is also the CSI utilized on the BS for efficient allocation of the resources to the users. The sampled CSI values depend on the adopted PDP. On a time basis, subcarrier gains are independent, but the PDP model and hence its statistics remains the same. A methodology for generating the sampled channel gain values is described in [27], and this technique was followed in our work. The minimum time resolution of the system equals to one OFDM symbol. Users' instantaneous channel gains are perfectly known both at the transmitter and receiver ends. The former allows the BS to allocate available resources (Power, Subcarriers, and Modulation Modes or Bits) according to the CSI. The latter aids channel estimation and coherent reception of the transmitted symbols. Moreover all the subcarriers are used to convey data symbols whereas in practical systems pilot symbols occupy part of them (guard and DC bands also exist). Bits are modulated based on an adaptive M–QAM scheme with M taken values from the set D = $\{2,4,\ldots,M_{max}\}$, hence each OFDM symbol can carry up to $N\times\log_2(M_{max})$ bits (system hard capacity). Additionally, since a single-cell network is studied, only thermal noise quantified by a constant Power Spectral Density N_0 is taken into account and no inter-cell interference is present.

As far as the resource allocation model the following assumptions hold: (a) a subcarrier can not be shared by more than one user during one OFDM symbol, but it can be assigned to different users in different OFDM symbols. This scheme eliminates intra-cell interference, (b) transmission power is distributed among the subcarriers and a fixed instantaneous sum-power constraint holds, and (c) adaptive uncoded modulation per subcarrier is performed. The resource allocation information is transmitted to the terminals through an error-free and zero-delay signalling channel. By perfectly predicting the future CSI, there is no need for implementing a retransmission mechanism (ARQ) which decays system throughput. Moreover no error correction coding (FEC) is applied.

Regarding the MAC-layer model we consider a simple queuing system assuming a single FIFO infinite queue for each user. Packets arrive to the system's queue at a constant rate since CBR packet flows have been assumed for the reason of simplicity. Packet Scheduling, described in Section IV, regulates the dequeueing of packets and data transmissions over the OFDM air interface by selecting and prioritizing the corresponding users at each time symbol or frame. A block diagram of the system model is depicted in Figure 1.

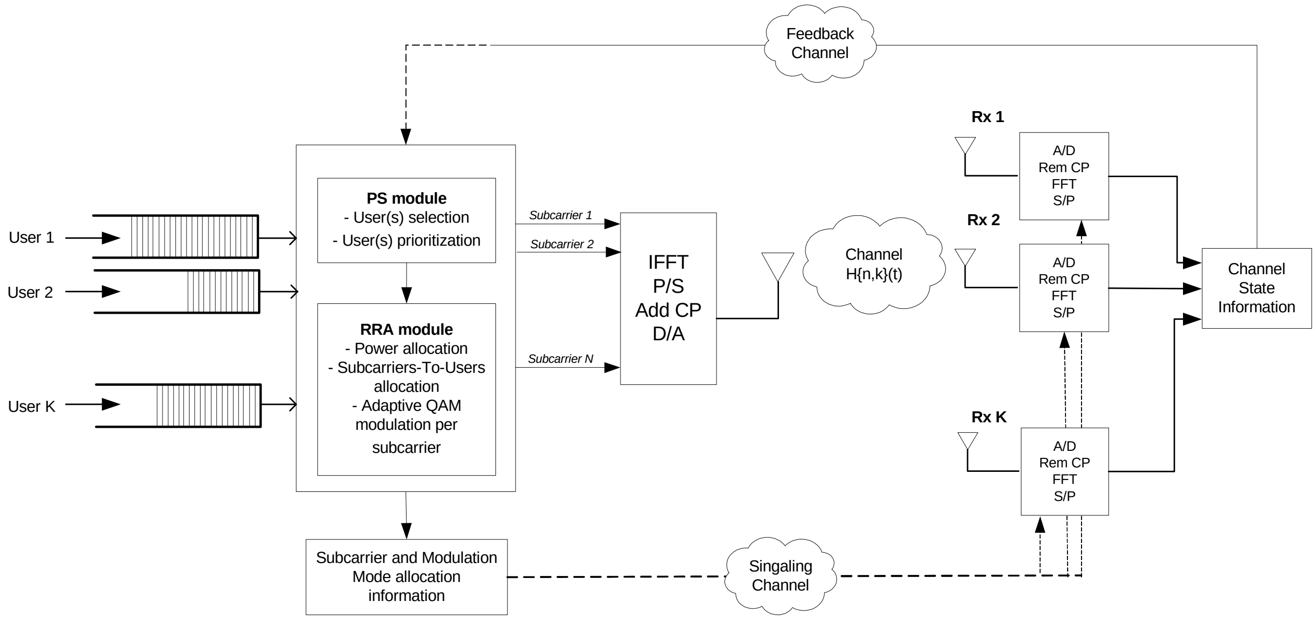

Figure 1. System Model

III. PHY–CENTRIC RADIO RESOURCE ALLOCATION

A. *Framework and Problem Formulation*

Radio Resource Allocation mechanisms aim at distributing the available shared resources to the competing users. In general RRA is responsible for optimizing PHY-Layer transmissions, that is, both the objective and the constraints of the formulated problem are PHY-centric. Usually either average spectral efficiency or transmission power constitute the objective function, while minimum target BER (or equivalently received SNR), PHY data rate and peak transmission power comprise the system constraints. Concepts such as system/users' average throughput, delay or fairness are not taken into account. Based on this aspect, an infinitely backlogged traffic model per user is adequate for the performance evaluation study of these techniques [28].

The BS is responsible for the allocation of available radio resources to the users on an OFDM symbol-by-symbol time scale. A decision algorithm (also called loading algorithm) must determine (a) the number of the subcarriers allocated to each user, (b) which subcarriers must be given to each user, (c) the distribution of the total available transmission power to the users/subcarriers, and (iv) the modulation mode of each subcarrier (also called bit loading). Two possible formulations are found in the bibliography; the Margin Adaptive approach where the transmitted power is kept as low as possible while individual rate constraints are satisfied (preferred for CBR traffic flows) and the Rate Adaptive approach where sum-rate is maximized under individual rate requirements and fixed total power (preferred for VBR traffic flows). Given the bandwidth-rate adaptive nature of multimedia traffic, RA approach seems to be more attractive allowing for VBR transmissions, dynamic

$$\max R_{tot}\left(\rho_{n,k}, c_{n,k}\right) \text{ where } R_{tot}=\sum_{n=1}^{N}\sum_{k=1}^{K}\rho_{n,k}\cdot c_{n,k} \quad \text{(O.F.)}$$

$$s.t.\ R_k \ge R_k^{\min}\ \forall k\ (C.1) \text{ where } R_k=\sum_{n=1}^{N}\rho_{n,k}\cdot c_{n,k}$$

$$P_{tot}\le P_{\max}\quad (C.2) \text{ where } P_{tot}=\sum_{n=1}^{N}\sum_{k=1}^{K}\rho_{n,k}\cdot P_{\min}(c_{n,k}) \qquad (1)$$

$$\sum_{k=1}^{K}\rho_{n,k}=1\ \forall n\ (C.3)$$

$$c_{n,k}\in\left\{0,1,...,\log_2\left(M_{\max}\right)\right\},\ \rho_{n,k}\in\left\{0,1\right\},$$

$$P_{\min}(c_{n,k})=\frac{N_0 BW}{\left|H_{n,k}\right|^2}\cdot\frac{1}{3}\left[Q^{-1}\left(\frac{BER_k^{\min}}{4}\right)\right]^2\cdot\left(2^{c_{n,k}}-1\right)$$

resource distribution and higher bandwidth utilization. Therefore, in the context of this work the RA problem will be studied.

Next we mathematically formulate the RA problem. We define $\rho_{n,k}$ (being zero or one) and $c_{n,k}$ (in bits/subcarrier/OFDM symbol units) the subcarrier assignment and the modulation mode indicator variables where *n* and *k* are integers spanning from 1 to N and 1 to K (N is the number of subcarriers and K is the number of users) correspondingly. If $\rho_{n,k}$ is one then the nth subcarrier is assigned to the kth user whereas $c_{n,k}$ contains the number of bits/symbol (constellation size) assigned to the n[th] subcarrier. Therefore the problem under study can be mathematically formulated as in (1). (C.1) and (C.2) constraints are obvious. $P_{\min}$ in (C.2) expresses the minimum required power in order to load the n[th] subcarrier with $c_{n,k}$ bits/symbol and transmit them to the k[th] user under a predefined target BER. This function depends on $c_{n,k}$, the channel gain for the specific subcarrier–user combination (which is known at the BS) and the modulation/coding technique employed in the system. $P_{\min}$ can be calculated by link level Monte Carlo simulations [27], closed-form analytical expressions where it is allowed (e.g. [25]) or approximative numerical expressions. Since we assume that no coding technique is performed and bits are mapped to a QAM constellation we use the approximate formula given from [29] which is derived based on the "single-channel gap analysis". (C.3) constraints reassure that there is no subcarrier sharing between users in one OFDM symbol.

By solving the above problem we obtain $\rho_{n,k}$ and $c_{n,k}$ for all *n* and *k* and then the resource allocation is completed. One can easily observe that (1) is in fact a large-scale nonlinear integer optimization problem and can be solved using methods from the optimization theory (see for example [30]). The sum-rate corresponds to the objective function and rate, power and subcarrier expressions in (C.1) – (C.3) to the problem constraints. These methods are usually complex and although they provide the optimum resource allocation, it is prohibitive to apply them in a real system.

A typical system scenario consisting of 250 subcarriers, 10 users and 8 possible modulation modes corresponds to an optimization problem of 5,000 unknown variables (2×N×K), 261 (N+K+1) constraints and a 0-1 design space. In order to deal with this complexity disjoint approaches are applied, that is, subcarrier, power and modulation mode allocation are performed independently, leading to suboptimum but practically implementable solutions. In the next subsection algorithms for obtaining the problem solution found in the bibliography will be presented and evaluated in terms of maximum sum-throughput performance. This list of algorithms is not exhaustive, but includes the most representative ones. This study will give an insight for the possible incorporation of RA optimization schemes in a dynamically evolving system.

B. Algorithms

1) Integer/Linear Programming Based Optimum Solutions: In [13] and [14] the authors provide the framework for obtaining the optimum solution of problem (1). The original problem is transformed to a binary linear integer programming (BLIP) maximization problem by introducing a new indicator variable. The solution of the new problem determines the optimum power, subcarrier and bit allocation. Substituting this solution into the objective function, we get the maximum achievable throughput. There exist several techniques for solving this binary IP problem ($R_{tot,IP}^*$), such as exhaustive enumeration or branch and bound [30], [31]. The main drawback of these methods is their high complexity; therefore an alternative technique is highly needed and the linear relaxation is often used towards this purpose. Any LP technique, such as the large-scale linear interior point method [32] can be applied to the relaxed problem, however, the optimum solution of the relaxed problem ($R_{tot,LP}^*$) will be higher than that of the IP problem, thus, an upper bound for the resulted sum-rate is actually acquired. Nevertheless, the LP allocation cannot be directly implemented in an OFDM system since subcarrier sharing and non-feasible QAM constellation selection may be parts of the solution. In any case, solutions $R_{tot,IP}^*$ and $R_{tot,LP}^*$ will be used as reference values for comparison with practical algorithms which will be presented in the next sections.

2) Two Step Algorithm: In [16] a two step suboptimum approach for solving the RA problem is proposed. First the number of subcarriers and the total power allocated to each user are calculated ("resource allocation" phase). A greedy algorithm is presented, based on the rate requirement and the average channel profile of each user. The second phase ("subcarrier assignment and bit loading") constitutes the subcarriers-to-users allocation and the modulation mode selection for each subcarrier. The authors do not specify how the per user power must be distributed among its subcarriers, so we assume an equal distribution. Based on this fact and perfect knowledge of the channel, then for a target received BER, the achievable rate for all subcarrier-user combinations can be calculated utilizing the inverse of the $P_{\min}$ function.

Therefore, the modulation mode selection need not be calculated and the original problem is transformed to a special format, known as the "assignment problem". The optimum solution to the assignment problem is obtained by the "Hungarian" algorithm (see [32] for details). Compared to the IP/LP optimum algorithms the resulted total rate is expected to be lower, so as the execution time. The reason is that the initial allocation phase is based on the average channel conditions per user, a metric that often fails on "capturing" the strong frequency selectivity of the wireless medium. Other proposed metrics, include the geometric mean, or the mean of the strongest subcarriers. However, the "Hungarian" algorithm implementation is computationally expensive as well, something that affects the complexity of the whole algorithm.

TABLE I
SYSTEM PARAMETERS FOR THE RRA SIMULATION RUNS

Quantity	Symbol	Value/Comment Set (1)	Value/Comment Set (2)
Bandwidth	BW	2.5 MHz	2.5 MHz
Number of subcarriers	N	250	250
OFDMA symbol time	T_s	100 μsec	100 μsec
Modulation modes	D	M–QAM, $M = 2^n$ where $n \in \{1,\ldots,\infty\}$	M–QAM, $M = 2^n$ where $n \in \{1,\ldots,8\}$
Target BER	P_e	10^{-6}	10^{-6}
Number of Users	K	2 – 18	10
Users' Distribution	-	Uniform	Uniform
Cell radius (circular)	R_{cell}	2000 m	2000 m
Maximum Transmitted Power	P_{max}	3.5×10^{-3}W or WSNR = 25 dB	Controlled in order to have WSNR from -5 to +40 dB
Thermal Noise Density	N_0	-174 dBm/Hz	-174 dBm/Hz
Required Rate Per User (CBR)	R_u	(1000bits/OFDM symbol)/K (totall rate = 50% of System Load)	20 - 180 bits/OFDM symbol (10% - 90% of System Load)
Channel Model - Large Scale	-	Log-Distance Path Loss: n = 4, d_0 = 10 m, f_c = 2 GHz Lognormal Shadowing : σ = 10 dB	Log-Distance Path Loss: n = 4, d_0 = 10 m, f_c = 2 GHz Lognormal Shadowing : σ = 10 dB
Channel Model - Small Scale	-	Exponential PDP , 4 μsec delay spread	Exponential PDP, 4 μsec delay spread

3) Optimum solution assuming equal power allocation for all subcarriers: Assuming equal power allocation (E.P.A.) among the N subcarriers in (1), the $c_{n,k}$ variables can be precalculated from the inverse of the $P_{\min}$ function. E.P.A. assumption is justified in [15] and its references therein. Substituting the $c_{n,k}$ values into (1), a linear integer programming problem is obtained with regard to the subcarrier assignment variables $\rho_{n,k}$, and the number of unknown variables is decreased by a factor of two. The IP solution ($R_{tot,EPA,IP}^*$) and the LP relaxed one ($R_{tot,EPA,IP}^*$) for the transformed problem serve as upper bounds for any algorithm that follows this assumption. It is expected, however, that these sum-rates will be lower than that of the optimum solution under unequal power allocation.

4) Iterative suboptimum algorithm assuming equal power allocation for all subcarriers: In [15] a reduced complexity joint subcarrier and bit allocation algorithm is proposed. The authors adopt the equal power allocation assumption and then they develop an iterative subcarrier allocation technique. Initially, the subcarriers are allocated to the "best" users in order to maximize the total throughput ignoring the individual rate constraints. It is easy to show that this is achieved by allocating each subcarrier to the user who supports the maximum rate (or has the best CSI) for a target BER on it. The initial allocation is followed by a subcarrier reallocation procedure. In essence, users' spare resources (if any) are reallocated to unsatisfied users, based on a strategy that keeps the number of these operations as low as possible. The authors claim that the performance loss of this algorithm compared to the optimum one (algorithm 3) is only 0.5%.

C. Performance Evaluation

1) Maximum Achievable Performance of various RRA optimization algorithms: A comparison performance study of the above algorithms in terms of the maximum achieved cell throughput is presented in this subsection. We assume that no outage occurs, namely, all the examined algorithms are able to guarantee the minimum required rates for all the users, and then assign the rest system resources targeting to the maximization of the sum-rate function. An infinite-backlogged queue model is also adopted and no maximum mode is suggested; thus maximum spectral efficiency is limited by the BS power availability. 8 simulation scenarios are executed by varying the number of users per cell from 6 to 18 with a step of 2. In order to have comparable results we assume that at each scenario the total required rate is constant and set at 1000 bits/OFDM symbol, and for this reason we alter accordingly the required rate per user. Users are spread uniformly in the cell and do not move, and 1000 OFDMA symbols are simulated and averaged per scenario. A summary of the simulation parameters is given in TABLE I - set 1. The LP-based optimum solution ("OptLP") and the LP-based under equal power allocation solution ("OptLPEPA") serve as upper bounds for the two practical algorithms (2-step or "Yin" and the iterative suboptimum one assuming equal power allocation or "Zhang"). The optimum solutions are obtained through the implementation of a large-scale interior point method [33]. The IP-based optimum solutions are not obtained since they require extremely high computational effort. Besides, the LP solutions express the upper bounds. Concerning "Yin", an implementation of the "Hungarian" algorithm is needed, like the one presented in [35].

Moreover two simple algorithms are devised for comparison purposes: The first one is called "Best

TABLE II
SUMMARY OF RADIO RESOURCE ALLOCATION ALGORITHMS

Algorithm	Tool(s) for solving the OP	Performance	Complexity
Opt(LP)	Branch & Bound, Relaxed LP	Optimum (IP), Upper Bound (LP)	Extremely High
Opt(LP)EPA	Branch & Bound, Relaxed LP	High	High
Zhang	Iterative greedy algorithm	High, Very close to OptEPA	Medium to Low (due to step 2)
Yin	Greedy, Hungarian algorithm	High	Lower than Opt, Still High due to the hungarian algorithm in step 2
Base	-	Very Low	Negligible
BC	Simple Ordering Method	Upper Bound, not a feasible solution	Medium to Low (due to waterfilling)

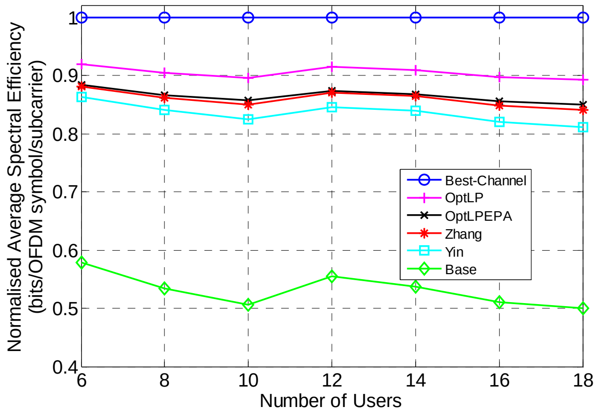

Figure 2. Performance comparison of RRA algorithms

Channel" and assigns each subcarrier to the "best" user in terms of achievable rate. Then the waterfilling algorithm is applied to the assigned subcarriers completing the power and bit loading. This algorithm provides the maximum achievable sum-rate but there is no minimum rate guarantee. It is a stricter bound than the one obtained by the "Opt" algorithm and determines the actual instantaneous sum-capacity of our system. For further details the reader can refer to [36]. The other algorithm is based only on individual rate requirements and not on channel state, and is used in order to evaluate the gain of opportunistically exploiting frequency selectivity and multi-user diversity. This scheme called "Base" assigns to each user an amount of the available subcarriers and power that are proportional to its rate requirements (ratio of individual rate requirement divided by the total rate requirements). Then for each user, the power is equally split among its subcarriers and the maximum achievable rate is computed based on the inverse of the P_{min} function. The subcarriers are allocated to the users orderly. The computational complexity of the specific approach is obviously negligible.

The sum-rate performance in bits/OFDM symbol/subcarrier for the above algorithms is shown in Figure 2. We have normalized the results by dividing them with the Best-Channel performance, since this is the actual capacity of the system at each scenario. This depends on the applied simulation setup and the available BS power. We first observe a significant 60 % gain on average of the channel-aware practical algorithms ("Yin" and "Zhang") compared to the rate-only based one ("Base"). This is justified by the fact that these algorithms tend to allocate to the users their "best" (in terms of achieved rate) subcarriers and also the calculation of the amount of allocated resources per user is more advanced than that of the "Base" algorithm. The inherent complexity of these schemes is therefore counteracted by their significant performance gain. "Zhang" algorithm performance loss compared to the optimum solution under equal power allocation is only 0.6 % while its complexity is significantly lower. "Yin" algorithm performs worse compared to the "Zhang" and also the use of the "Hungarian" algorithm for the subcarrier assignment phase raises significantly its complexity. The performance loss of "Yin" algorithm compared to "Zhang" is 3%, but still is better than "Base" by 57%. Finally, we must point out that the throughput loss of "Yin" and "Zhang" compared to the upper bounds obtained by the LP-based optimum solution under unequal power allocation is only about 5 and 8% correspondingly. Taking into consideration both the computational burden and the throughput performance of the examined algorithms, we can select the "Zhang" algorithm as the most appropriate dynamic RA scheme on an OFDM symbol-by-symbol or frame-by-frame basis. A summary of the above findings is given in TABLE II.

2) Dynamic Channel-aware and Static RRA Performance Comparison: Next we focus on estimating the gain of applying advanced channel-aware resource allocation schemes (like the algorithms presented above) in comparison with simple and computationally inexpensive static schemes for more practical cases. This study is necessary, since the introduction of such channel-aware techniques in a real network increases both signaling and system complexity significantly; hence, spectral efficiency or outage improvement must be significant as well. Based on the observations of the initial performance study, "Zhang" scheme will be adopted as the dynamic RRA scheme, due to its excellent performance and low complexity and the "Base" algorithm as the static RRA scheme. The latter scheme distributes power and subcarrier resources to the users proportionally to their static PHY data rate requirements without taking into account any information about users channel states.

A set of simulation runs is executed in order to evaluate cell throughput and outage for several worst-case SNR (WSNR) and minimum system load (L_{GBR}) values. "WSNR" expresses the minimum possible SNR occurring at the cell-edge, when only path-loss is taken into account [11]. Apparently, it is directly related to the total transmission power constraint, but it is a more general metric as it also includes the cell radius effect. On the other hand the term "load" is used to describe the ratio of the total minimum rate requirements to the cell hard capacity, which in turn is determined by the number of subcarriers and the maximum supported rate per subcarrier. We assume that each user has infinite data to sent, therefore, if minimum rates are satisfied, the remaining resources can be assigned to any user. WSNR parameter is related to soft-resources (power) while system loading to hard-resources (subcarriers). The simulation parameters are given in TABLE I - set 2 while results are depicted in Figure 3 - Figure 6.

Based on the above graphs several interesting conclusions could be drawn, regarding sum-rate (or equivalently cell throughput) and outage performance. First, we observe that "Base" algorithm sum-rate performance is insensitive to different loading conditions while outage increases with heavier loading **(**Figure 5, Figure 6**)**. The former is justified by the fact that resources are equally split among users in all cases since individual minimum required rates are identical for all users; the latter by the fact that as target minimum rates increase and the available power is constant more users become unsatisfied. In addition, sum-rate and outage performance improves as WSNR increases for any loading condition, since it is the available power that actually determines the achieved average cell-capacity.

On the other hand, "Zhang's" scheme improves cell-outage performance and sum-rate (except for some extreme cases which will be described below) by exploiting the CSI knowledge and assigning the "best" resources in terms of achieved rate or consumed power to each user (Figure 3, Figure 5). A general observation is that the average sum-rate increases by 6.1 – 50.8 % for varying WSNRs and 19.5 – 30.9 % for varying offered loads when channel-aware RRA is applied.

We can also observe that the gain acquired by assigning resources based on CSI is highly dependent on the system WSNR (or available BS Power) and Loading situations. First, observing the "low WSNR-low Load" operating region (WSNR< 5 dB and $L_{GBR} \leq 10\%$) we could conclude an extremely high sum-rate gain which reaches almost 150% at 0 dB, but at the same time the average achieved sum-rate by the Zhang scheme is relatively low. Actually the MAC-aware-only scheme is on outage at this region, failing to satisfy minimum rate guarantees. The specific gain is caused by the elimination of outage when exploiting the CSI of the users, but the shortage in available BS power constrains the total sum-rate to values lower than 5.5 bits/OFDM symbol. When more BS power becomes available (medium-to-high WSNR), cell throughput increases significantly reaching 8 bits/OFDM symbol but the channel-aware RRA gain decreases and finally diminishes when WSNR approaches 15 dBs. This happens because at this region ("high WSNR-low Load"), Zhang's algorithm is limited by the maximum modulation mode which prevents assigning more bits to efficient subcarriers. Therefore a MAC-aware-only strategy can be applied at this case under no performance loss.

On the other hand when the minimum required load increases (40–70% of system capacity) a similar performance is observed, although cell-throughput saturation or equivalently sum-rate gain minimization appears at higher WSNR values (18 and 20 dB for 40 and 70% system loading correspondingly). This behavior can be explained by the shifting of the corresponding outage curve to the right as loading increases (Figure 4). Another important observation is that at high-to-medium loading situations the maximum channel-aware RRA gain is lower compared to the light loading case, assuming that no outage occurs (Figure 3). For example at 10% minimum required load state, maximum gain is 150% (at a WSNR of 0 dB) whereas for 40% and 70% loads this gain drops to 25% and 5% correspondingly. As minimum required loading increases, the flexibility of a channel-aware scheme is reduced since constraints satisfaction (minimum rates) and not the maximization of the objective function (sum-rate) dominates the search for the solution of the optimization problem. A summary of the above findings is given in TABLE III and a general remark is that both BS power availability and minimum required loading have a serious effect on the actual system performance in terms of throughput or probability of outage.

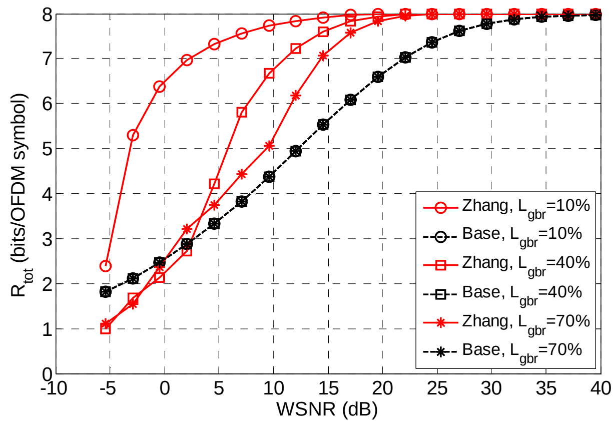

Figure 3. Throughput Performance versus WSNR of Channel-aware and Static RRA for various system loading values

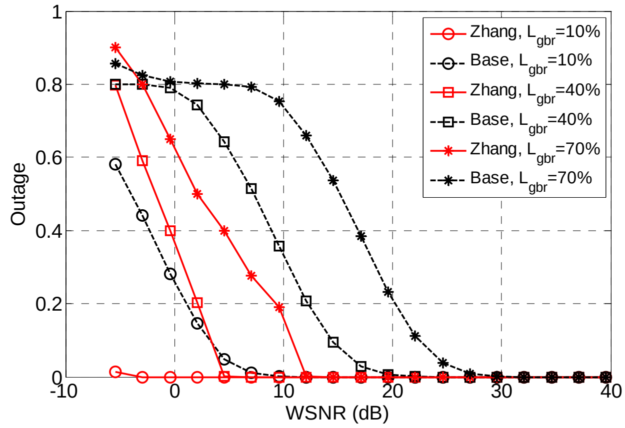

Figure 4. Outage Performance versus WSNR of Channel-aware and Static RRA for various system loading values

TABLE III
SUMMARY OF DYNAMIC CHANNEL-AWARE RRA SIMULATION RESULTS

Operating Region	Throughput Gain	Channel-aware Sum-Rate
Low Power – High GBR Load (-3 dB, 90%)	≈ 0 %	1.35 bits/OFDM symbol/subcarrier
Low Power – Low GBR Load (-3 dB, 10%)	158 %	5.4 bits/OFDM symbol/subcarrier
High Power – High/Low GBR Load (35 dB, 90/10 %)	0.5 %	8 bits/OFDM symbol/subcarrier

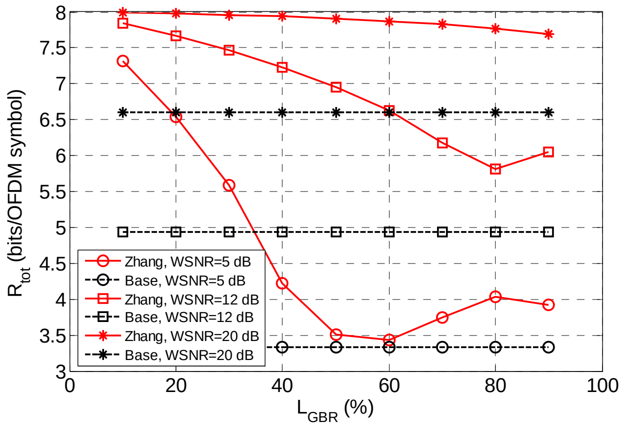

Figure 5. Throughput Performance versus System Loading of Channel-aware and Static RRA for various WSNR values

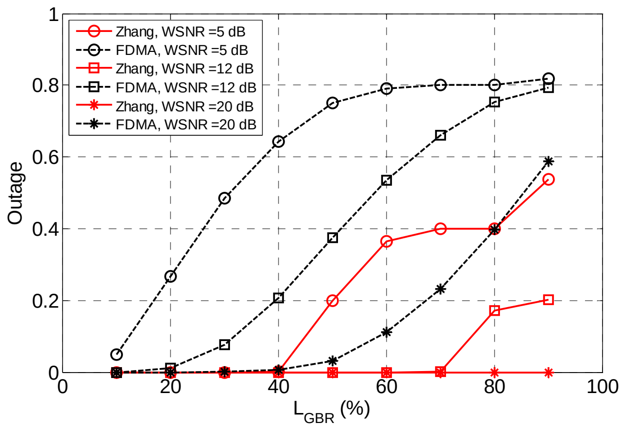

Figure 6. Outage Performance versus System Loading of Channel-aware and Static RRA for various WSNR values

IV. MAC – AWARE RESOURCE ALLOCATION / PACKET SCHEDULING

A. Motivation

PHY-centric QoS metrics such as minimum BER and PHY data rate were examined, and suitable rate adaptive (RA) resource allocation mechanisms attempting to satisfy them have been presented so far. Nevertheless, MAC-layer QoS, that is, average packet throughput, delay and fairness, reflects users' satisfaction and network efficiency more precisely. Traditionally, Packet Scheduling (PS) is the MAC-layer entity which controls packet-level QoS by dividing air interface capacity, monitoring queues, and prioritizing users or traffic flows [19]. PS schemes become particularly important in the context of next generation mobile networks relying on OFDM radio technology; inevitably, the PS would be a cross-layer entity. Efficient allocation of subcarriers to different terminals requires the exploitation of PHY-layer Channel State Information (CSI), while user prioritization and resource partitioning relies heavily on QoS related MAC-layer information, like delays and queues length. As presented in Section III, strategies developed so far treat the whole problem as an optimization problem formulated in different ways reflecting the adopted constraints and objectives. However, all these algorithms provide optimum or suboptimum distribution of radio resources in the frequency and power domains based on a theoretical infinitely backlogged queue model and do not take into account the corresponding QoS issues. Moreover, the actual performance of an OFDMA-RRA scheme depends largely on the interaction between PHY-layer oriented RRA, MAC-layer PS and higher layer telecommunication traffic [23]. In this context, the evaluation presented in Section III, provides an upper bound of the actual performance in a real system.

In fact, under the conventional rate adaptive approaches, resource allocation is considered as a "static" optimization problem in the sense that the problem constraints are fixed and the dynamic evolvement of the system in the time domain is not considered. Hence, resource demands in terms of data rate per user are assumed to be constant which results in great inefficiency when VBR multimedia or bursty internet traffic is assumed. Even in the case of CBR traffic, the current static rate and margin adaptive approaches result in performance degradation since possible temporal congestion situations - due to severe channel fading or user distribution at the cell edge – will introduce queuing and consequently, variable over time capacity demands. Furthermore, standard OFDMA-RRA schemes do not consider congestion situations, since they assume adequate resource availability to guarantee the feasibility of the optimization problem.

To overcome these limitations, enhance the system performance and provide an insight for the actual system utilization, we devise a joint PHY–MAC layer system model for single-cell OFDM packet networks. Inside this system model, a cross-layer dynamic packet scheduling scheme is being implemented incorporating the following features:

a) QoS awareness through MAC-layer info usage in the scheduling discipline
b) PHY-centric optimized performance through frequency-selective scheduling (or equivalently

TABLE IV
PACKET SCHEDULING SCHEMES CONSIDERED FOR EVALUATION

Dynamic OFDM RRA algorithm	Frequency Selective Scheduling ("Zhang")	Adaptive Optimization Constraints	SNR scheduling in Time Domain
Static RA	✓	-	-
SNR Enhanced Static RA	✓	-	✓
Dynamic RA	✓	✓	-
SNR Enhanced Dynamic RA	✓	✓	✓
FDMA SCHEMES (BASE)			
Dynamic FDM	base EPA	✓	-
SNR Enhanced Dynamic FDM	base EPA	✓	✓

RRA) in the frequency domain and SNR-based scheduling in the time domain

B. Proposed OFDMA Packet Scheduling Schemes

The proposed PS schemes are mainly based on the OFDMA-RRA philosophy; essentially the conventional resource allocation scheme is extended in order to take into consideration QoS issues, leading to a MAC-aware RRA approach. Based on the analysis and simulation results in Section III, "Zhang" scheme has been adopted for the evaluation. However, the qualitative analysis presented subsequently is not affected, if any other RA scheme assumed. In this work we introduce an adaptation of RA called "Dynamic RA" scheme. According to this approach the minimum rate constraints of the conventional RA scheme are tuned dynamically based on instantaneous required rate for each user. This MAC triggered adaptation of problem constraints, transforms the original but complex VBR allocation problem to multiple consecutive CBR instances which is simpler to solve. As it will be demonstrated in the following subsection, our approach outperforms the traditional RA schemes in terms of system throughput and packet delays.

Furthermore we exploit the possibility to perform joint time - frequency scheduling to further enhance the performance of the proposed scheme. As stated in [8] the average system performance is maximized considering the time varying channel conditions (SNR-based scheduling). In order to incorporate the time diversity of radio channel into our scheme we introduce to the standard scheme a dynamic opportunistic user prioritization according to the instantaneous user channel gains. For the prioritization, the instantaneous frequency-averaged channel gains are taken into account. Figure 7 depicts the functionalities of the proposed PS scheme. Note that for the performance evaluation procedure of the next subsection we have considered five alternative algorithms with features summarized in TABLE IV. "Base" frequency scheduling algorithm (or simplified FDM) differs from the base algorithm mentioned in the previous section: first equal power allocation among subcarriers is assumed, so the maximum supportable rate per subcarrier for each user can be calculated. Then subcarriers are swept and are assigned to the users one-by-one until individual target rates are satisfied. Therefore it is more "clever" than the previous basic static RRA algorithm, and "Zhang's" throughput gain is expected to be lower.

C. Performance Evaluation

1) Comparative Evaluation study of the proposed modificitations: We first devise the corresponding PS algorithms incorporating some or all of the proposed modifications and compare them in terms of the achieved throughput and delay. A summary of the simulation parameters is given in TABLE I. Additionally, CBR flows of 100 kbps with a packet size fixed at 180bits/packet have been assumed. The frame duration was set to 10msec and consists of 10 OFDM symbols (these parameters correspond to a constant requirement of 100 bits/OFDM symbol/user). 1000 runs are executed and the average throughput and packet delay is obtained for each algorithm under different system loading. In this subsection we compare the PS Schemes summarized in Section IV.B. Since the static algorithm deals with the CBR allocation problem we have also considered CBR packet flows throughout the simulation campaign in order to derive consistent and comparable results. However, the performance gain introduced in the case of VBR flows is expected to be larger. Moreover, transmitted power is large enough in order to approach system hard capacity (WSNR is approximately 50 dB).

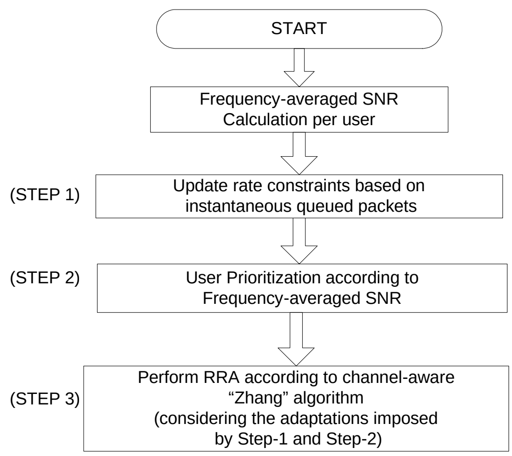

Figure 7. Flowchart of the Proposed PS modifications

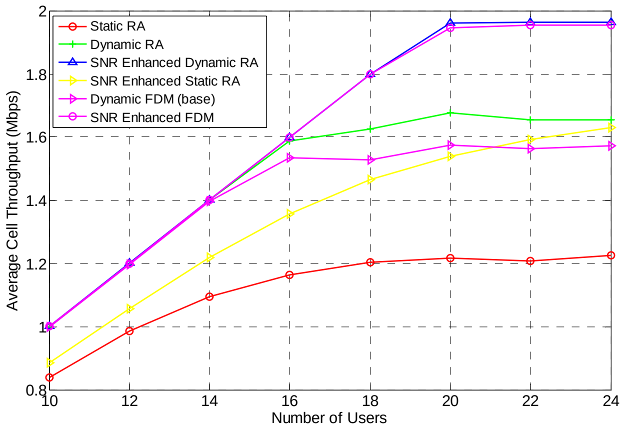

Figure 8. Throughput performance of static and dynamic RRA schemes

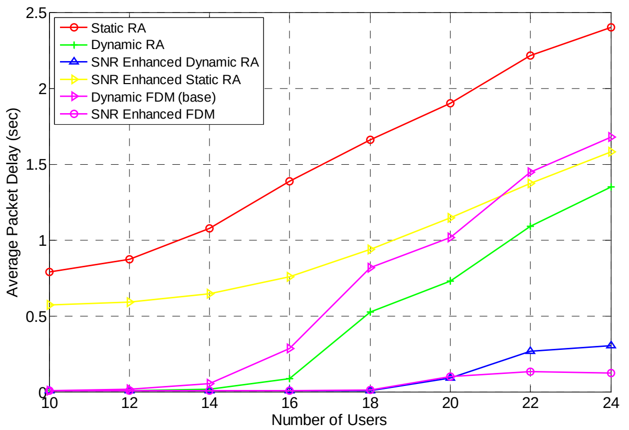

Figure 9. Delay performance of static and dynamic RRA schemes

Figure 8 and Figure 9 demonstrate the Cell Throughput and Packet delays performance for all PS schemes. As it is demonstrated in Figure 8 static RA scheme achieves relatively low utilization, around 60% of the total cell capacity. Furthermore, as it is depicted in Figure 9, this scheme introduces great inefficiency and large packet delays even at low cell loading. This is due to the static nature of the algorithm which is not able to handle the dynamic over time evolvement of the system, introducing infeasible states to the optimization problem (e.g. when severe channel fading leads one or more users to outage). Fortunately, the Dynamic RA scheme dramatically increases the performance, achieving cell utilization around 83% under high cell loading. As a result delay performance is also improved accordingly. In the following analysis only the dynamic approach will be considered due to its great efficiency compared to the static schemes.

Furthermore, Dynamic RA scheme outperforms the base Dynamic FDM scheme (throughput gain around 6%) meaning that the frequency selective scheduling (considered in Zhang's algorithm) will be beneficial for OFDM packet Scheduling. However, notice that the obtained gain using our joint MAC-PHY layer system model is much lower that that obtained in Section III (around 22%). That means that conventional MA and RA evaluation studies serve as performance upper bounds providing the theoretical maximum of cell capacity.

Finally, as it is shown in Figure 8, the incorporation of SNR scheduling in the time domain further enhances the performance of Dynamic RA scheme achieving a performance gain around 18% with a system utilization of 96% which is very close to the total cell capacity of 2Mbps. However, when SNR scheduling is considered in the time domain, the gain of frequency selective scheduling is marginal, around 0.8%.

2) Study of the effect of PS strategy, System Loading and BS power on the Throughput Performance: The conclusions above, indicate that the gain of frequency selective scheduling over a standard and static FDMA approach depends on various parameters like system loading, power availability and time domain scheduling scheme that is also considered in the resource allocation strategy. In this section we demonstrate - via computer simulations – the impact of all these parameters on the achieved gain when frequency domain scheduling is considered. In the previous section only max SNR (or under different notation C/I) time scheduling was considered, a scheme that is likely to be unfair in terms of resources distribution. Here, we will utilize a famous fairness scheme as well, namely Proportional Fair PS. The results of our simulations are depicted in Figure 10 and Figure 11, where the simulation setup is the same with the previous subsection, except for the system capacity that has been set to 20 Mbps.

Based on these figures several interesting conclusions can be derived. First of all it is clear that whatever PS scheme is considered in the time domain (Proportional Fair or C/I-based for example) the throughput gain depends on the power availability. Note that in our simulations under C/I-based time scheduling an average gain of 6% can be achieved through frequency scheduling. However, note that as power availability increases the expected gain decreases. Particularly for normalized power (or equivalently WSNR) equal to 1 we observe a gain around 17%, but this gain decreases down to 0.5% for normalized power equal to 5.4. This is a quite reasonable result, since high power availability means that more subcarriers become "good" for any user and thus the throughput gain decreases.

Additionally, the achieved throughput gain depends on the system loading. Higher system loading, means that more resources are used in order to guarantee the minimum user rate constraints. Hence a limited number of resources (subcarriers) can be assigned to "good users". Specifically at lower system loading (10 active users) we observe an average throughput gain around 15 % but this gain decreases to 6% at higher system loading (13 active users). Finally, we observe that the throughput gain achieved through frequency scheduling depends on the considered PS scheme on the time domain. In this study we have considered two representative scheduling algorithms: an opportunistic C/I based Scheme focusing on maximizing cell throughput and a proportional fair (PF) scheme focusing both on

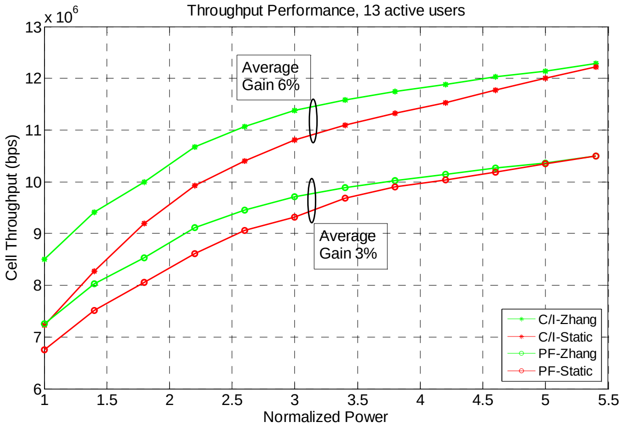

Figure 10. Cell Throughput vs BS Power for High Loading

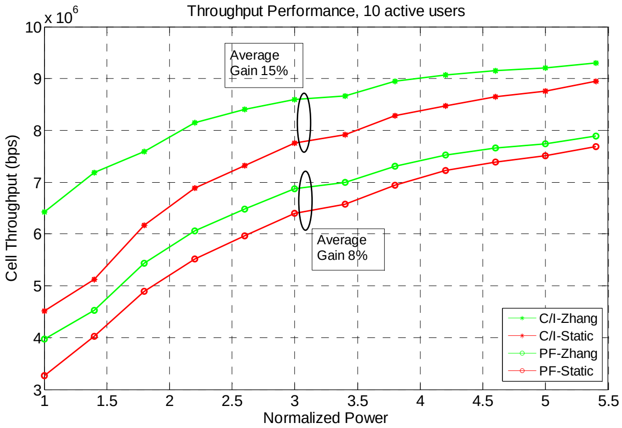

Figure 11. Cell Throughput vs BS Power for Lower Loading

throughput optimality and user rate fairness. As a closing remark, frequency scheduling offers higher throughput gains when combined with opportunistic scheduling in the time domain rather that when combined with proportional fair schemes. Under opportunistic scheduling and high system loading an average gain of 6% can be achieved while this gain decreases to 3% under proportional fair scheduling.

V. CONCLUSIONS – FUTURE WORK

In this paper optimum and practical suboptimum radio resource allocation algorithms for single-cell OFDMA networks have been evaluated and various enhancements for current schemes have been introduced. The proposed schemes outperform the conventional ones in terms of throughput and packet delays. The incorporation of MAC-layer info as well as SNR/PF scheduling in the time domain dramatically improves the performance. However, under SNR time scheduling the incorporation of frequency selective scheduling provides marginal gain for the high transmitted power case. Furthermore, our joint PHY-MAC simulation study shows a much smaller performance gain of standard RA than the gain obtained through PHY layer oriented studies found in the literature.

Various issues remain unclear and must be thoroughly examined; here we describe several basic ideas. First, the interaction between packet scheduling and resource allocation considered in this work is PHY-centric. Despite the fact that PS and RRA modules are designed independently, a joint consideration (tight coupling) could lead to further performance enhancement. Moreover, additional PHY issues such as practical imperfect channel quality estimation, coding and subchannelization must be studied. Regarding MAC layer, consideration of advanced PS mechanisms such as minimum guaranteed bit rate (min GBR), and modified largest weighted delay first (M-LWDF) [20] and their interaction with different RRA algorithms needs substantial study. Finally, system behavior in terms of throughput, delay and fairness under realistic mixed traffic conditions (delay-sensitive VBR and best effort data) is an important matter as well.

ACKNOWLEDGMENT

The authors wish to thank Dr. Niclas Borlin for providing us with an implementation of the “Hungarian” algorithm. This work is part of the 03ED184 research project, implemented within the framework of the “Reinforcement Programme of Human Research Manpower” (PENED) and co-financed by National and Community Funds (20% from the Greek Ministry of Development-General Secretariat of Research and Technology and 80% from E.U.-European Social Fund).

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