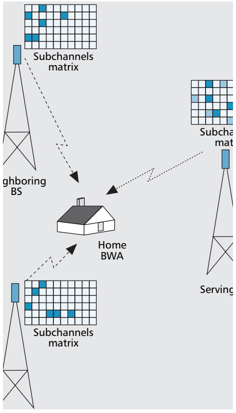
ON THE IMPACT OF PHYSICAL LAYER AWARENESS ON SCHEDULING AND RESOURCE ALLOCATION IN BROADBAND MULTICELLULAR IEEE 802.16 SYSTEMS

LEONARDO BADIA, IMT LUCCA INSTITUTE FOR ADVANCED STUDIES
ANDREA BAIOCCHI AND ALFREDO TODINI, UNIVERSITY OF ROME "LA SAPIENZA"
SIMONE MERLIN, SILVANO PUPOLIN, ANDREA ZANELLA, AND MICHELE ZORZI,
UNIVERSITY OF PADOVA



Multi-cellular networks based on the IEEE 802.16 standard appear to be very promising candidates to provide end-users with broadband wireless access. However, they also pose interesting challenges.

ABSTRACT

Multicellular networks based on the IEEE 802.16 standard appear to be very promising candidates to provide end users with broadband wireless access. However, they also pose interesting challenges in terms of radio resource management, where several design choices are not specified in the standard, intentionally left open to implementors. For this reason, we focus in this article on scheduling and resource allocation, and investigate how they could operate in a cross-layer fashion. In particular, we describe the principles of joint scheduling and resource allocation for IEEE 802.16 operating in AMC mode, and discuss the critical role played by physical layer considerations, especially intercell interference estimation and channel state awareness, in the obtained performance. This leads to identifying key open issues and possible general solutions.

INTRODUCTION

Among the emerging technologies for broadband wireless access (BWA), IEEE 802.16 is one of the most promising and attractive, but also presents very challenging aspects. Expected areas of applications of the IEEE 802.16 technology include high-speed Internet access, public services, private networks, and broadband backbones for regions where wireless coverage is limited and deployment of cables would be too expensive or impractical. It is often believed [1, references therein] that a very important scenario, and probably the first to exploit IEEE 802.16, will be the provision of BWA for moderate mobility environments such as residential Internet connections or offices. In this setting a multicellular deployment based on IEEE 802.16 technology may be envisioned, where fixed access points play the role of base stations (BSs), which is the scenario we focus on in this work. The conclusions we reach provide useful insights on other scenarios as well (e.g., a wireless backhaul realized through IEEE 802.16 as well as the coexistence of these two systems).

The IEEE 802.16 air interface standard [2] describes in detail the physical (PHY) layer, based on orthogonal frequency-division multiplexing (OFDM). In particular, we focus on the multiple access (OFDMA) with adaptive modulation and coding (AMC) mode of IEEE 802.16, which appears to be the most suitable for our study. This method uses adjacent subcarriers to realize subchannels, and results in a hybrid frequency-/time-division multiple access (FDMA/TDMA) medium access scheme. When used with fast feedback channels, it can assign a modulation and coding combination per subchannel, enabling "water-pouring" types of algorithms, and can also be used effectively with the adaptive antenna system (AAS) option [2]. In the standard technical specifications, for such a scenario several issues regarding scheduling and resource allocation algorithms are intentionally left open to developers, which stimulates researchers to seek strategies capable of providing better performance.

In this article we discuss the challenges presented by packet scheduling and resource management, and explore the design of a joint scheduler/resource allocator; we do not investigate optimization issues, focusing instead on

This work was partially supported by the Italian Ministry of University, Research and Education (MIUR) through the PRIMO project [3] as part of the FIRB program.

 1536-1284/07/$20.00 © 2007 IEEE

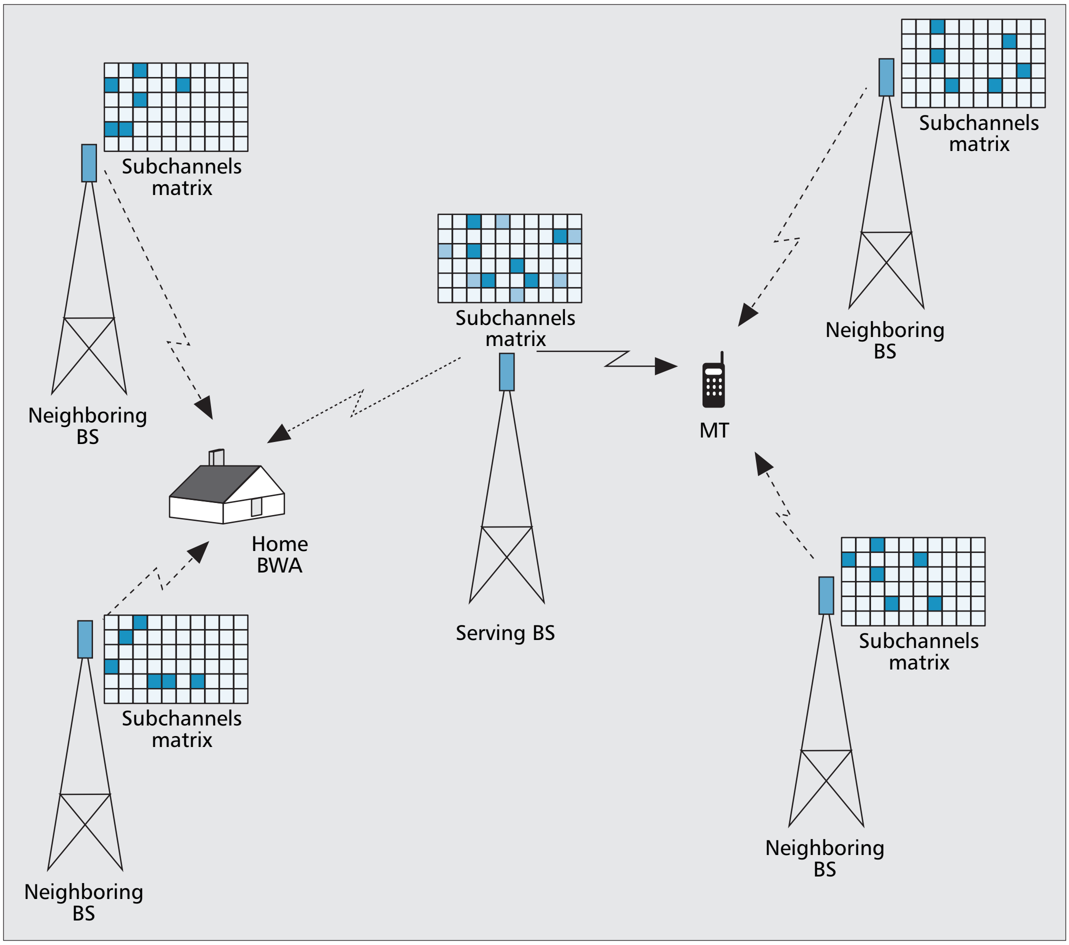


Figure 1. *System scenario.*

In these studies, the impact of other interfering cells is neglected, whereas in the system under examination full frequency reuse is envisioned and therefore the allocation of packets may be greatly affected by the interference conditions in the assigned resource.

effective and simple implementation choices. The first contribution of this article is therefore to outline a modular scheme where a credit-based scheduler is integrated with an efficient resource allocator based on a low-complexity power-efficient and capacity-driven heuristic criterion. Although these algorithm components are not themselves new, our original contribution is their integration in a modular framework, which is one of the main outcomes of the research project PRIMO [3]. As shown in the following, our scheme is also able to provide tunability in the trade-off between overall power expenditure and time to achieve fairness among users. This is possible by regulating the degree of freedom in the allocation, which is managed through proper information exchange between the scheduling and resource allocation modules.

Another contribution of our research is the analysis of interference issues arising in this scenario. Even though there are studies proposing similar approaches, where packet scheduling and resource management are jointly addressed to have efficient solutions (e.g., [4]), for most of them the analysis and performance evaluation are conducted in a simplified single-cell scenario. In these studies the impact of other interfering cells is neglected, whereas in the system under examination here full frequency reuse is envisioned, and therefore the allocation of packets may be greatly affected by the interference conditions in the assigned resource. We believe that this fact requires careful design of system management that is both channel- and interference-aware, in order to properly allocate the resource and obtain an efficient implementation of IEEE 802.16-based BWA. In this context we present and discuss the outcome of simulations obtained with realistic models for the details of OFDM and the physical propagation scenario, explicitly considering multicell interference.

For ease of presentation, in the following we first describe the considered system, and subsequently discuss the issues arising from the proposed scheduling and resource management strategy. We finally show numerical results, supporting our general conclusions on the relevance of channel state and interference awareness.

System Framework

The reference system framework is described in the following. We consider the forward link of a multicellular system as in Fig. 1, where a complete reuse of the available time-frequency resources among neighboring cells is assumed. This is one of the most challenging aspects, and requires an accurate investigation when performing resource allocation.

The resource access in each cell is organized as a hybrid OFDMA-TDMA, which corresponds to an IEEE 802.16 system in the OFDMA-AMC mode. Bandwidth is divided into N_s subcarriers, and a timeframe consists of N_t subsequent OFDM

Our approach can be regarded as loosely cross-layer, trying to strike a balance between flexibility and modularity, as achieved by strict hierarchical layered design, and optimized performance, as could be yielded by cross-layer algorithms.

symbols. In order to reduce the resource addressing space, channel coherence in frequency and time is exploited by grouping adjacent ⟨subcarrier, time slot⟩ pairs to form a logical subchannel, which is the minimum allocable unit of resource. The addressing space is thus reduced to M_s subchannels in frequency and M_t slots in time. Each subchannel can be assigned to a different user and be independently bit and power loaded. In order to make use of this flexibility in resource management, channel and interference measurements need to be exploited by scheduling and allocation algorithms.

We assume that in each frame the BS has perfect knowledge of the channel status and interference value for each subchannel of each user, as measured in the previous frame. This can be obtained, say, by piggybacking such information in each uplink packet. Due to the dynamics of the propagation environment and the interference scenario, this information is only an estimate of the channel status in the upcoming frame, which makes the proposed framework suitable for slowly varying channels.

The system is loaded with best effort traffic modeled by a constant bit rate source associated with each user. At the beginning of each frame the BS collects the physical layer and traffic information, which is passed to the resource management block.

From a cross-layer perspective, resource management could be pursued by a joint optimization of all the free allocation variables, that is, which users to schedule, jointly with their power levels, subcarriers, and timeslots, under quality of service (QoS)/fairness constraints for traffic scheduling and signal-to-noise ratio (SNR)/bit error rate (BER)/power constraints at the physical layer. However, this would lead to a complex algorithm design, merging physical layer optimization goals with traffic level requirements and involving a large number of variables and parameters. This approach would also lose any flexibility if new traffic requirements or different optimization goals for the physical layer were to be considered (e.g., as a consequence of the introduction of new technologies).

Hence, our approach can be regarded as *loosely cross-layer*, trying to strike a balance between flexibility and modularity, as achieved by strict hierarchical layered design, and optimized performance, as could be yielded by cross-layer algorithms.

Radio resource allocation is aware of all physical layer constraints and can be given a desired physical transmission related optimization target. It aims at carrying a given traffic backlog of data units (basic transport unit, BTU, in the following). To a radio resource allocator, it is irrelevant which BTUs are the "hottest" or most valuable to carry and from which flow queue they should be taken. This is the point at which a traffic scheduler comes in. Our basic idea is to define the overall cross-layer resource management so that scheduling and allocation algorithms can be changed without impacting each other, provided that the common data structures are kept.

The coupling between scheduler and allocator is realized through a list of BTUs, ordered according to the scheduling criteria, along with global parameters specifying handling constraints for those BTUs. The list is defined frame by frame, and is processed by the allocator to define which input traffic to assign to each frame. After allocation and transmission, it is up to the allocator to update the status of the BTUs of the current list as delivered, transmitted but failed, or not allocated at all. This feedback is used by the scheduler to update its own internal state and to provide a new list; the scheduler should also be given information about the maximum expected achievable capacity for each user, so as to make sensible scheduling decisions. Other common parameters, as detailed in the next two sections, make this a crosslayer approach, yet there is sufficient decoupling between BTU scheduling and radio resource allocation algorithms that they can be internally modified independent of each other. As an example, if the leading criterion for scheduling is changed from, say, non-weighted fairness to delay deadline matching, this will affect the way the BTU list is formed in each frame, but the allocation algorithm can be kept the same, as long as its objectives (i.e., minimize transmission power or achieved BER) make sense for the application scenario. The resource management architecture just described is schematically represented in Fig. 2.

Scheduling Framework

Scheduling algorithms for packet-switched networks have the goal of achieving a fair allocation of the bandwidth resources to the flows competing for access to the shared medium. The basic packet scheduling schemes were originally proposed for wireline networks, where the channel is usually assumed to be error-free and of constant capacity [5].

In wireless networks scheduling algorithms aim at fair allocation of resources, while attaining high system throughput and low power consumption; if fairness constraints were not taken into account, mere throughput maximization would have an extremely unfair outcome, where few users (those enjoying good channel conditions) are repeatedly allocated most of the bandwidth while the rest starve. Known packet scheduling schemes have been extended to wireless networks by taking into account the additional feature of a strongly time-varying channel [6]. In the case studied in the present article, it is unrealistic to pursue short-term fairness, since scheduling users experiencing bad channel states benefits neither their own flow nor the aggregate network throughput. It has long been recognized that a better policy is to allow for some short-term unfairness in order to improve efficiency. The scheduler keeps track of how much each flow is allowed to transmit, and compensates lagging flows when their channel conditions improve or they have been starving for too long; thus, the goal remains that of attaining fairness, but over a longer timescale. To implement this, the scheduler needs to take into account both channel and traffic state information; hence, it is assumed that the BS is aware of the queue states of all of its users, and that a sufficiently accurate estimate of the channel state is available; this is easy to achieve if the channel measurement feedback delay is small compared to the rate of variation of the radio channel. For example, frequent feedback messages could be sent, quantized in such a way that only few bits are needed to describe the channel state level.

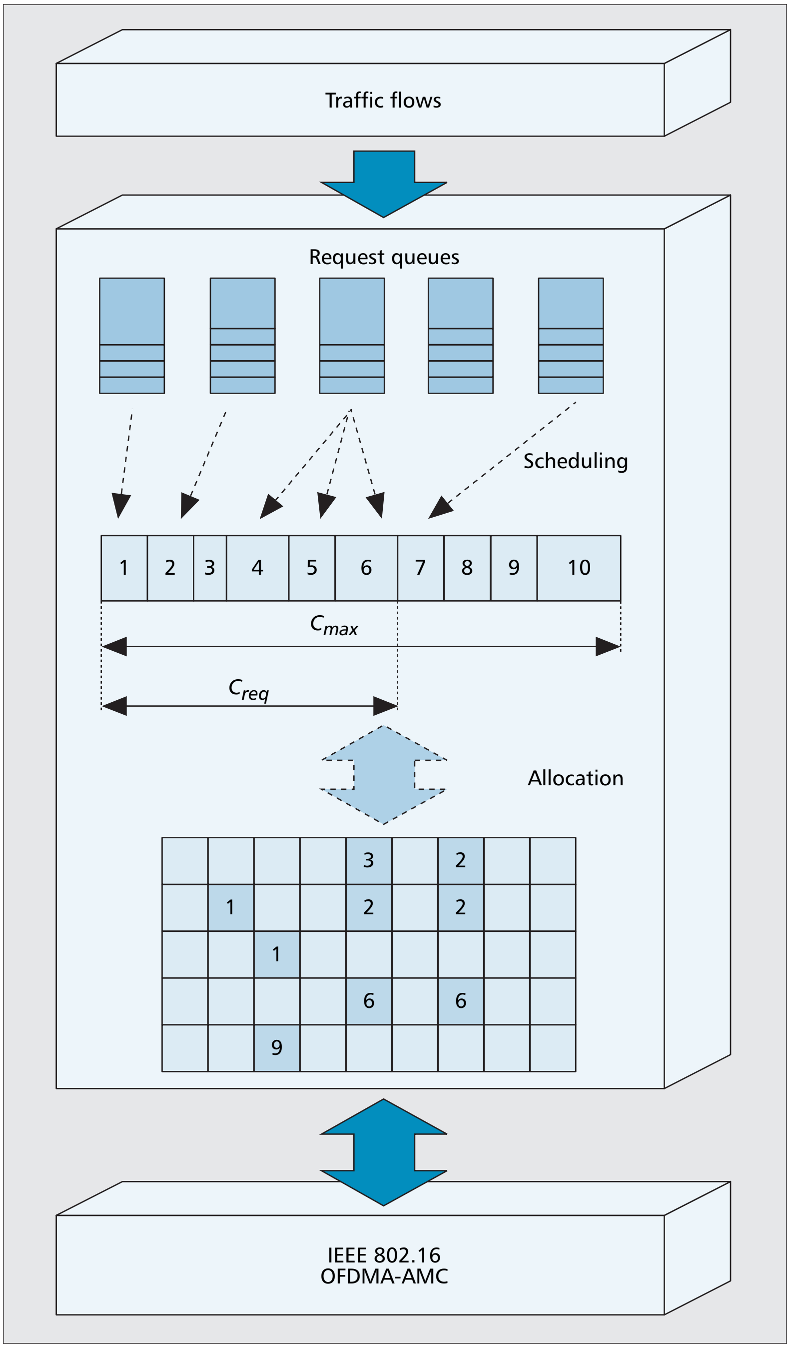
Some mechanism to keep track of the service state of each flow must be present. Many packet scheduling algorithms proposed in the literature rely on the time provided by a common reference clock; packets are tagged according to the clock time as they enter the queues. The next packet to transmit is selected by taking the time tag and the packet length (and thus the packet transmission time) into account [7]. However, virtual-time-based algorithms have high computational complexity, which makes their implementation difficult and expensive. Thus, algorithms based on credits, such as Credit-Based Fair Queuing (CBFQ) [8], have been proposed; they are simple and computationally efficient, achieve fairness among flows, and can be adapted to work in a wireless environment (e.g., WCFQ [9]). In credit-based algorithms, the service state of each flow is summed up by a single number: its credit value. A flow gains credits when it is not scheduled and uses credits when it is scheduled. This scheme makes it easier to take a continuous channel model into account; for example, in WCFQ channel quality is dealt with by introducing a cost that depends on the state of the channel, and the scheduling priority of a flow depends on both the amount of credits it has cumulated and its channel quality. A flow experiencing a bad channel is at first prevented from transmitting; it is scheduled again when either its channel quality has improved or it has accumulated enough credits to overcome its bad channel quality index.

Packet schedulers described in the literature have traditionally been designed for TDMA systems, where the goal of the scheduler is to select one flow at a time for transmission. Thus, such solutions did not tackle the problem of simultaneously scheduling packets belonging to different flows and allocating a pool of transmission resources among them. This is the scenario we have to deal with in IEEE 802.16. In the modular scheduler-allocator architecture based on a cross-layered approach proposed in the previous section, the packet scheduler passes some packets to the radio resource allocator (RRA), which in turn determines how to transmit them. A suitable scheduler is obtained by putting a simple but efficient credit-based counter in a feedback loop with the underlying RRA. The additional physical layer information used by our scheduler implies that it can be seen as an *opportunistic scheduling* mechanism [10].

As discussed earlier, the scheduler and allocator are two separate modules, whose implementation details are transparent as long as the interface between them remains the same. This differentiates our scheme from other recent proposals, such as [11], where a joint MAC/PHY optimization is performed.

The interaction between the scheduler and the RRA takes place in two steps: *request selection* and *resource allocation*. Both steps require cooperation of the scheduler and allocator. First of all, a parameter $C_{req} \leq 1$ is evaluated, which represents the desired aggregated load of the cell, normalized to the maximum allocable rate and computed according to an estimate of the actual frame capacity; in order to control the intercell interference, C_{req} should be less than 1. In the selection step, the flows to be scheduled in the frame are selected, together with the fraction of transmission resources (number of subchannels) to allocate to each flow. The selection is made starting from a list of requests produced by a simple credit-based packet scheduling algorithm, taking into account the average throughput achieved by each flow in the past. This list is passed to the resource allocator, which determines which requests should be satisfied, giving priority to the flows currently experiencing favorable channel conditions relative to their average path gain. Thus, in this step we aim at reducing power consumption (as well as interference) by exploiting time diversity.

The scheduler parameter C_{max} determines the aggregate size of the requests in the list, normal-



■ **Figure 2.** *Scheduling/allocation framework.*

The resource allocation mechanism deals with physical layer issues and its goal is to pursue efficiency in the resource usage in terms of power consumption, interference rejection or capacity provisioning. Its behavior depends on the scheduling decision.

ized to the value of C_{req}; thus, a higher value of C_{max} results in a longer request list, provided that each flow has enough backlogged traffic. In general, $C_{max} \geq 1$, and the greater the value of C_{max}, the higher the degree of freedom left to the allocator in selecting the flows to be scheduled. If $C_{max} \gg 1$, no fairness is sought, but simply the best users are allocated; at the other extreme, when $C_{max} = 1$, all selected requests must be allocated regardless of their channel conditions; this ensures the fairest possible outcome, even if over a very short time span some degree of throughput unfairness can still be observed due to channel errors and the granularity of the allocation.

Once the requests to allocate have been selected, the resource allocation algorithm determines *which subchannel* should be assigned to each flow. In this second step, we aim at exploiting *frequency diversity*, which is one of the features of the OFDMA radio interface.

It is important to point out that the way the selection and allocation of the requests are performed by the allocator has an impact on the performance of the system only in terms of power consumption and throughput achieved; it has no impact on long-term fairness among flows, which is guaranteed by the credit-based scheduling algorithm employed to create the request list.

Resource Allocation Issues

The resource allocation mechanism deals with physical layer issues, and its goal is to pursue efficiency in resource usage in terms of power consumption, interference rejection, or capacity provisioning. Its behavior depends on the scheduling decision, since it imposes some constraints on the physical resource usage optimization; thus, the two operations are strictly related. RRA has to jointly manage the following allocation variables:

- Subset of data requests to actually be transmitted, selected from the request list provided by the scheduler
- Which subchannel <subcarrier, timeslot> to allocate to the selected data
- Which power to use on the selected subchannel
- Which bitload to use on the selected subchannel

The variability of channel conditions can be exploited by opportunistically allocating the resources to a subset of users that have the best conditions. This property is usually referred to as *multiuser diversity* [12].

Depending on the channel model, each user can experience a different channel attenuation on each subchannel, which in our case is represented by a <subcarrier, time slot> couple. This degree of freedom is usually referred to as *frequency and time diversity*.

In general, in the allocation of each user the selection of the channel, power level, and bitload to assign are strictly interrelated. The AMC option available in the OFDMA mode of the IEEE 802.16 standard offers high flexibility and efficiency in this sense. The optimum solution of scheduling/allocation problems would require joint selection of all the optimum parameter values, which is very challenging and, in most cases, impractical.

Several algorithms have been proposed to solve this problem, mainly based on heuristic approaches in order to obtain reasonable computational complexity [13]. It should be noted that in a general multicellular system, due to the mutual interference among cells, the assignment of all the allocation variables is a network-wide operation. An optimal solution in general requires complete network knowledge and a centralized allocation algorithm, and is therefore not feasible from a practical point of view, so that distributed optimization problems have been proposed [14].

In the proposed framework, each cell performs its own resource allocation without explicit control information exchange with neighboring cells. The only information used refers to the channel and interference value measurements provided to the BS by its own mobile terminals (MTs).

As described earlier, the scheduling algorithm determines the aggregated throughput to be loaded on the cell and passes to the RRA a tentative list of data requests to be scheduled. Since the length C_{max} of this list (which specifies all the requests available for allocation) can be greater than C_{req} (which determines the number of requests that can actually be allocated), RRA has some freedom in selecting the subset of requests to transmit. Clearly, RRA selects such a request subset in order to maximize the advantages of multiuser diversity.

The aim of the proposed approach is to maximize the aggregated capacity on each frame by using a low complexity algorithm. Here, we briefly describe the allocation heuristic in order to give some insight on the problem and draw interesting conclusions on the joint scheduling/allocation. Let $k \in \mathcal{K}$ denote the user and $\langle s, t \rangle$ the subchannel. Let $c_{k,s,t}$ be the Shannon capacity referred to the specified user and subchannel. At the first step, a maximum power level for each subchannel is fixed so that the maximum Shannon capacity $c_{k,s,t}$ corresponding to each subchannel for each user can be computed based on the channel and interference information.

Each user, and thus each request, is associated a metric stating its goodness in terms of available capacity. At each step the request with the highest available capacity among those that have not yet reached the minimum requested rate is selected for a subchannel assignment. Once the request to be served has been chosen, an efficiency metric ε is computed for each subchannel and each user:

$$\varepsilon_{k,s,t} = \frac{c_{k,s,t}}{\sum_{i \in \mathcal{K}} c_{i,s,t}}.$$

This index allows us to compare the advantage of allocating subchannel $\langle s, t \rangle$ to user k, rather than to any other request. The subchannel with the highest ε is associated to the request selected in the previous step. The bitload is set to the highest value less than or equal to $c_{k,s,t}$ among the available choices of coding-modulation formats, and the power is adjusted accordingly. This simple low-complexity heuristic acts in a greedy way by decoupling the assignment of each allocation variable. Even though this is a suboptimal optimization algorithm, it is shown to be able to exploit the multiuser and frequency diversity, and is thus suitable for our purposes.

Numerical Results

The proposed framework has been tested in a multicellular scenario where a nine-cell cluster is considered. The system has been set to work on a 5 MHz band with a 5 ms frame. According to the IEEE 802.16 standard this is compatible with a frame subchannel structure that consists of 16 AMC subchannels in the frequency domain and 24 slots in the time domain. In this case each subchannel consists of 24 adjacent data subcarriers in two adjacent symbols. The use of only one AMC format has been considered, corresponding to 144 b/subchannel. A time-varying and frequency-selective channel model, directly derived from the one proposed in COST-259 [15], has been used. The carrier frequency is in the 3.4 GHz range, and the path loss exponent has been set to $\alpha = 4$. A Doppler frequency corresponding to a speed of 1 m/s and a delay spread $\sigma_d = 50$ ns have been used.

For simplicity, in order to test the algorithm's behavior, the BS has been assumed to possess perfect channel and interference information for its mobile stations (MSs). The information is sent at the beginning of each frame, and refers to the measurements performed during the previous frame. To implement this exchange, several solutions are possible. In fact, the IEEE 802.16 standard provides several ways for the MS to send control information to the BS, allowing many levels of quantization and timing. The optimality of the allocation is a function of the amount of channel and interference information. Some preliminary evaluations of our scheme have shown that the overall signaling overhead, including this information as well as the broadcast of the schedule at the beginning of each frame, is limited to only a few percent.

A first consideration on the behavior of the joint scheduler/RRA refers to its ability to exploit the diversity naturally present in the system. In order to test whether the proposed framework is capable of taking advantage of the system's multiuser diversity, in Fig. 3 results for a scenario with a variable number of users are reported. A constant global amount of traffic requests, independent of the number of users, has been passed to the allocator. The behavior has been tested under two different values of the parameter C_{max}. Figure 3 shows that the average transmission power decreases as the number of users increases. The proposed algorithm selects the flows to be scheduled by taking into account their channel state, thus exploiting multiuser diversity. As a consequence, the greater the number of users, the greater the chance of being able to schedule a subset of users who are all experiencing good channel conditions, which results in lower transmission power requirements. If we only pursued efficiency, with no regard for fairness, the power reduction with a large number of users would be even more significant: only the best users would be allowed to transmit, while the others would be permanently blocked. This behavior is confirmed by the fact that the power consumption with $C_{max} = 1$ is higher than in the case when $C_{max} = 4$.

In the next set of results, we compare the power consumption and the fairness properties in order to point out that a trade-off exists and that the behavior of the proposed algorithm can be tuned by acting on the parameter C_{max}.

We quantify the achieved throughput fairness among traffic flows in terms of Jain's fairness index [16] for throughput, defined as $F = (\Sigma_{i=1}^{N} x_i)^2/(N\Sigma_{i=1}^{N} x^2_i)$, where x_i is the throughput

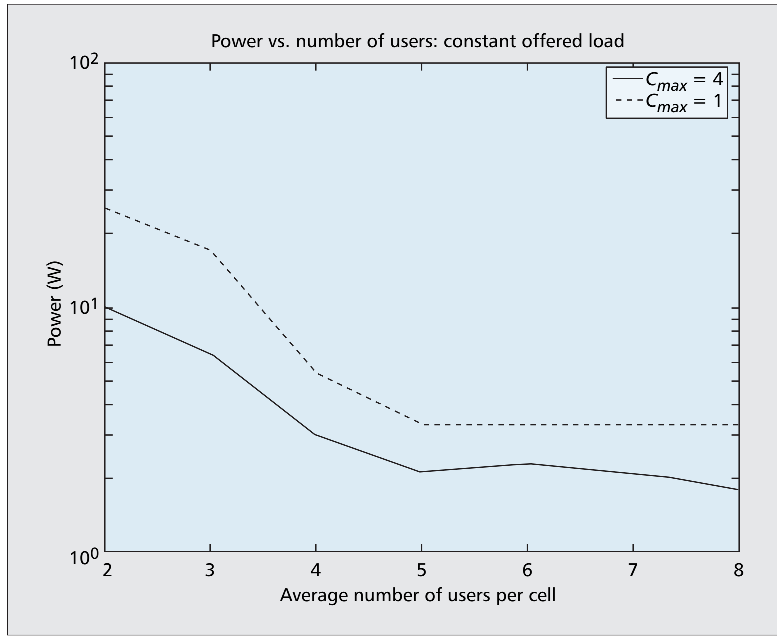


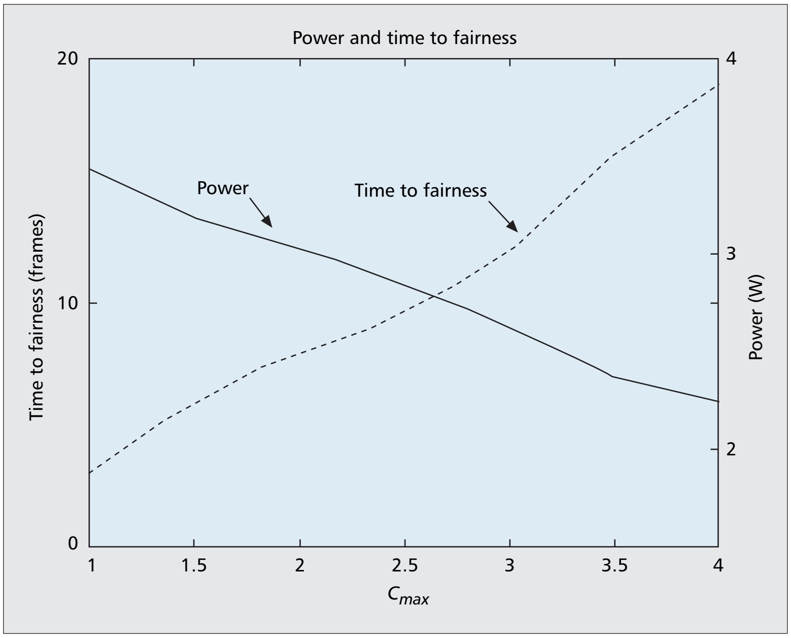
Figure 3. *Average cell power consumption vs. number of users for two values of* C_{max}.

achieved by flow i, and N is the number of competing flows. An index equal to 1 characterizes a perfectly fair outcome. We define the time-to-fairness metric (TTF) as the number of frames needed to reach a target fairness index, which has been fixed to 0.95.

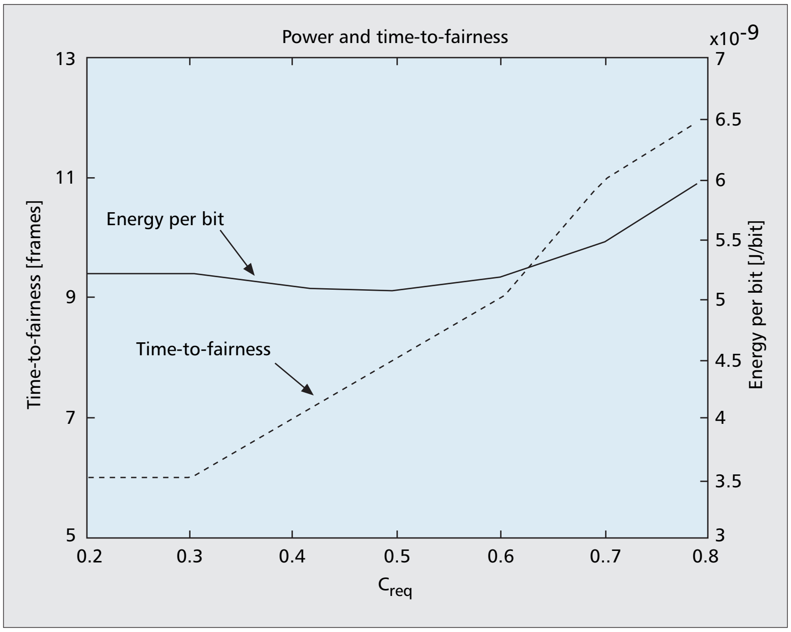
Figure 4 shows the mean transmission power and the TTF obtained with different values of C_{max} in a scenario with six users per cell on average and a fixed required capacity. The traffic sources are assumed to be in saturation (i.e., each terminal always has packets to transmit). As expected, the power decreases as C_{max} increases, while TTF increases. With $C_{max} = 1$ the allocator is forced to allocate all the requests selected by the scheduler, thus leading to the strictest possible fairness but with a power–inefficient allocation; as C_{max} increases, the allocator has a higher degree of freedom and can choose to allocate only the best users, which results in a higher power efficiency, but also in a higher TTF. However, it is remarkable that for any choice of C_{max} our algorithm is able to achieve high fairness after a number of frames, which is not very large (below 20 frames, i.e., 100 ms), even in cases of high C_{max}. This happens thanks to the exploitation of multiuser diversity with an intelligent time scheduling policy.

In Fig. 5 we plot the average energy per transmitted bit and the TTF vs. the normalized cell load C_{req}, with $C_{max} = 3$. The nearly constant per bit power consumption observed with our allocator is an indication that an intelligent allocation policy, which also takes interference into account, is able to manage the intercell interference by preferentially allocating less interfered resources. Anyway, as the cell load increases, the time needed to reach fairness increases.

Figure 6 shows Jain's fairness index, computed on a window of W frames, vs. the window size W, thus describing the fairness behavior of the algorithm in time. Two lower bounds are also shown. These lower bounds have been obtained by analytical formulas in [17], which are computed without taking into account the allocator policy, and are therefore valid for *any* resource allocation algorithm. The two curves, obtained with two different values of C_{max}, again show the effect of such parameter on fairness. The curve with the lower C_{max} (equal to 1.5) obtains a very high level of fairness already after few frames, whereas the curve with $C_{max} = 4$ exhibits a lower value of Jain's index, which also increases more slowly. Both curves asymptotically tend to perfect fairness ($F = 1$) in the long term, which confirms the goodness of our approach, which can trade off short-term fairness for power consumption by properly choosing the value of C_{max}.



■ **Figure 4.** *Average transmission power and TTF vs.* C_{max}*, normalized to* C_{req}.



■ **Figure 5.** *Average transmission power and TTF vs cell load, for* $C_{max} = 3$.

Conclusions

In this article we have discussed resource management aspects in a multicellular IEEE 802.16 network, where challenging optimization issues arise due to complete resource reuse among neighboring cells. In this context the OFDMA-AMC mode provided by the standard offers a flexible way to manage physical resources, leaving room for the development of efficient algorithms.

A framework for a completely distributed and dynamic resource management has been presented that merges traffic and physical level issues in a cross-layer perspective. Physical layer information, such as channel and interference measurements, together with traffic information, are exploited by the proposed two–layer algorithm in order to improve the performance.

In particular, simulations performed in a multicellular scenario have shown that the proposed joint scheduling and resource allocation algorithm is able to trade-off fairness requirements imposed at the flow level with physical efficiency metrics such as power consumption, and to exploit the diversity naturally present in the system, thus confirming that AMC-based resource management is an effective and promising approach for future generation wireless systems.

References

[1] C. Cicconetti *et al.*, "Quality of Service Support in IEEE 802.16 Networks," *IEEE Network*, vol. 20, no. 2, Mar.-Apr. 2006, pp. 50–55.

[2] IEEE standard for Local and Metropolitan Area Networks – Part 16: Air Interface for Fixed Broadband Wireless Access Systems, IEEE Std. 802.16, Rev. 2004, Oct. 2004.

[3] "PRIMO project — FIRB," http://primo.ismb.it/firb/index.jsp

[4] K. Taesoo *et al.*, "Design and Implementation of a Simulator Based on a Cross-Layer Protocol between MAC and PHY Layers in a WiBro Compatible IEEE 802.16e OFDMA System," *IEEE Commun. Mag.*, vol. 43, no. 12, Dec. 2005, pp. 136–46.

[5] A. K. Parekh and R. G. Gallager, "A Generalized Processor Sharing Approach to Flow Control in Integrated Services Networks: The Single-Node Case," *IEEE/ACM Trans. Net.*, vol. 1, June 1993, pp. 344–57.

[6] H. Fattah and C. Leung, "An Overview of Scheduling Algorithms in Wireless Multimedia Networks," *IEEE Wireless Commun.*, vol. 9, no. 5, Oct. 2002, pp. 76–83.

[7] S. Lu, V. Bharghavan, and R. Srikant, "Fair Scheduling in Wireless Packet Networks," *IEEE/ACM Trans. Net.*, vol. 7, Aug. 1999, pp. 473–89.

[8] B. Bensaou, D. H. K. Tsang, and K. T. Chan, "Credit-based Fair Queueing (CBFQ): A Simple Service-Scheduling Algorithm for Packet-Switched Networks," *IEEE/ACM Trans. Net.*, vol. 9, Oct. 2001, pp. 591–604.

[9] Y. Liu, S. Gruhl, and E. W. Knightly, "WCFQ: An Opportunistic Wireless Scheduler with Statistical Fairness Bounds," *IEEE Trans. Wireless Commun.*, vol. 2, no. 5, Sept. 2003, pp. 1017–28.

[10] G. Song and Y. G. Li, "Utility-Based Resource Allocation and Scheduling in OFDM-based Wireless Broadband Networks," *IEEE Commun. Mag.*, vol. 43, no. 12, 2005, pp. 127–34.

[11] Y. J. Zhang and K. Ben Letaief, "Energy-Efficient MAC-PHY Resource Management with Guaranteed QoS in Wireless OFDM Networks," *Proc. IEEE ICC*, May 2005, pp. 3127–31.

[12] P. Viswanath, D. N. C. Tse, and R. Laroia, "Opportunistic Beamforming Using Dumb Antennas," *IEEE Trans. Info. Theory*, vol. 48, no. 6, June 2002, pp. 1277–94.

[13] Y. J. Zhang and K. Ben Letaief, "Multiuser Adaptive Subcarrier-and-Bit Allocation with Adaptive Cell Selection for OFDM Systems," *IEEE Trans. Wireless Commun.*, vol. 3, no. 5, Sept. 2004, pp. 1566–75.

[14] G. Kulkarni, S. Adlakha, and M. Srivastava, "Subcarrier Allocation and Bit Loading Algorithms for OFDMA-Based Wireless Networks," *IEEE Trans. Mobile Comp.*, vol. 4, no. 6, Nov./Dec. 2005, pp. 652–62.

[15] L. M. Correia, Ed., *Wireless Flexible Personalised Communications – COST 259: European Cooperation in Mobile Radio Research*, Chichester, U.K.: Wiley, 2001.
[16] R. Jain, D. Chiu, and W. Hawe, "A Quantitative Measure of Fairness and Discrimination for Resource Allocation in Shared Computer Systems," DEC res. rep. TR-301, 1984.
[17] A. Todini *et al.*, "Cross-Layer Design of Packet Scheduling and Resource Allocation Algorithms for 4G Cellular System," *Proc. WPMC*, San Diego, CA, Sept. 2006.

BIOGRAPHIES

LEONARDO BADIA [M] (leonardo.badia@imtlucca.it) received a Laurea degree (with honors) in electrical engineering and a Ph.D. in information engineering from the University of Ferrara, Italy, in 2000 and 2004, respectively. During 2002 and 2003 he was on leave at the Radio System Technology Labs (now Wireless@KTH), Royal Institute of Technology, Stockholm, Sweden. After the Engineering Department of the Universita di Ferrara, he joined in 2006 the Institutions Markets Technologies (IMT) Lucca Institute for Advanced Studies, Italy, where he is currently a research fellow. He also collaborates with DEI, University of Padova, Italy. His research interests include energy-efficient ad hoc networks, transmission protocol modeling, Admission Control and economic modeling of Radio Resource Management for Wireless Networks. He serves also as reviewer for several periodicals in the communication area.

ANDREA BAIOCCHI [SM] (andrea.baiocchi@uniroma1.it) received his Laurea degree in electronics engineering in 1987 and his Dottorato di Ricerca (Ph.D. degree) in information and communications engineering in 1992, both from the University of Roma "La Sapienza," where he is currently a full professor in communications. His main scientific contributions are on traffic modeling and traffic control in ATM and TCP/IP networks, queuing theory, and radio resource management. His current research interests are focused on congestion control for TCP/IP networks and mobile computing, specifically TCP adaptation and packet scheduling over the wireless access interface. These activities have also been carried out in the framework of many national (CNR, MIUR) and international (European Union, ESA) projects, also taking on coordination and responsibility roles. He has published more than 70 papers in international journals and conference proceedings, has participated in the Technical Program Committees of several international conferences; he also served on the editorial board of the telecommunications technical journal published by Telecom Italia for 10 years. He serves currently on the editorial board of the *International Journal of Internet Technology and Secured Transactions* (IJITST).

SIMONE MERLIN [S] (simone.merlin@dei.unipd.it) received a Laurea degree in telecommunications engineering, magna cum laude, from the University of Padova, Italy, in 2004. He is currently a Ph.D. student in the wireless networking group at the University of Padova. His main research interests refer to cross-layer optimization in wireless ad hoc and cellular networks.

SILVANO PUPOLIN [SM] received a Laurea degree in electronic engineering from the University of Padova in 1970. He then joined the Department of Information Engineering, University of Padova, where he is currently a full professor of electrical communications. He is director of the Ph.D. School in Information Engineering and chairman of the board of Ph.D. School Directors of the University of Padova. He has been actively engaged in research on digital communication systems since 1970, covering the following topics: spread spectrum communication systems; design of large reliable communications networks; effects of phase noise and HPA nonlinearities in OFDM systems; 3G mobile radio communications systems (UTRA-FDD and TDD) and beyond (OFDM modulation and MC-CDMA); packet radio; and ad hoc networks. He spent the summer of 1985 at AT&T Bell Laboratories on leave from Padova, doing research on digital radio systems. He was General Chair of the 7th International Symposium on Wireless Personal Multimedia Communications (WPMC '04). He was principal investigator for national research projects "Variable Bit Rate Mobile Radio Communication Systems for Multimedia Applications," "OFDM Systems with Applications to WLAN Networks," and "MC-CDMA: An Air Interface for the 4th Generation of Wireless Systems," and was involved in the FIRB PRIMO Research Project "Reconfigurable Platforms for Broadband Mobile Communications."

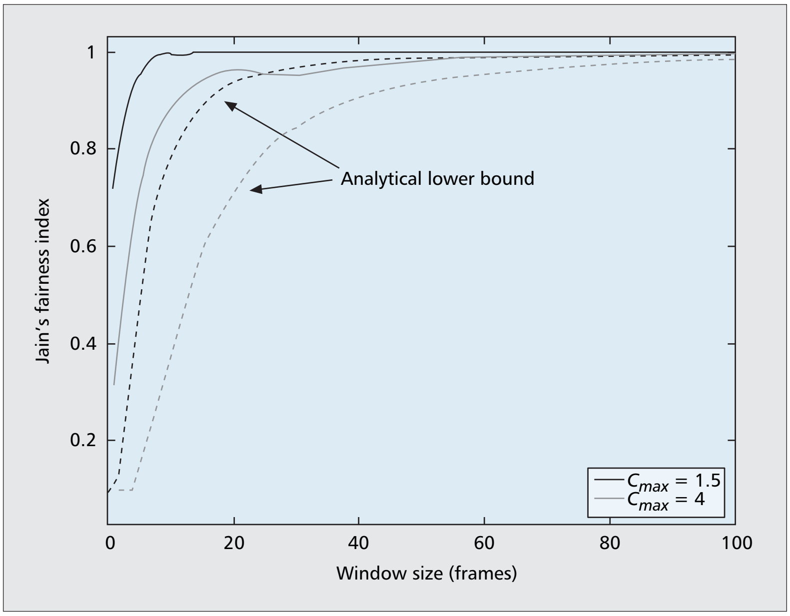


Figure 6. *Fairness achieved after each frame.*

ALFREDO TODINI (alfredo@net.infocom.uniroma1.it) received a Laurea degree in computer engineering, magna cum laude, and a Ph.D. in telecommunications engineering from the University of Roma "La Sapienza" in 2002 and 2006, respectively. He is currently a research fellow in the networking group of the Information Communications Department of the same university. His research interests include packet scheduling and resource management algorithms in wireless local area and cellular networks.

ANDREA ZANELLA [M] (zanella@dei.unipd.it) is an assistant professor at the Department of Information Engineering (DEI), University of Padova. He received a Laurea degree in computer engineering in 1998 from the same university and a Ph.D. degree in electronics and telecommunications engineering in 2002. Before that, he spent nine months as a visiting scholar at the Department of Computer Science of the University of California, Los Angeles, where he worked with Prof. Mario Gerla on wireless networks and wireless access to the Internet. His major research interest is in the field of protocol design and performance evaluation of WPANs, MANETs, VANETs and WSNs. He is a reviewer for several IEEE journals and international conferences in the ICT area. Furthermore, he is one of the main promoters and Program Chair of the Workshop on MultiMedia Applications over Wireless Networks (MediaWiN) and a TPC member of WPMC and EWSN.

MICHELE ZORZI [F] (zorzi@dei.unipd.it) received his Laurea and a Ph.D. degrees in electrical engineering from the University of Padova in 1990 and 1994, respectively. During 1992–1993 he was on leave at the University of California, San Diego (UCSD), attending graduate courses and doing research on multiple access in mobile radio networks. In 1993 he joined the faculty of the Dipartimento di Elettronica e Informazione, Politecnico di Milano, Italy. After spending three years with the Center for Wireless Communications at UCSD, in 1998 he joined the School of Engineering of the Universita di Ferrara, Italy, where he became a professor in 2000. Since November 2003 he has been on the faculty at the Information Engineering Department of the University of Padova. His present research interests include performance evaluation in mobile communications systems, random access in mobile radio networks, ad hoc and sensor networks, energy constrained communications protocols, and broadband wireless access. He was the Editor-in-Chief of *IEEE Wireless Communications* in 2003–2005, and currently serves on the Editorial Boards of *IEEE Transactions on Communications*, *IEEE Transactions on Wireless Communications*, Wiley's *Journal of Wireless Communications and Mobile Computing*, and the ACM/URSI/Kluwer *Journal of Wireless Networks*. He was also Guest Editor for special issues of *IEEE Personal Communications* (Energy Management in Personal Communications Systems) and *IEEE Journal on Selected Areas in Communications* (Multimedia Network Radios).