A Radio Resource Management Scheme Driven by Users' Preferences under the CSMA/CA Capacity Constraint

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Abstract— **In this paper we investigate the role of CSMA/CA capacity, having in mind in particular IEEE 802.11b Wireless LANs. We discuss a scheme where the trade-off between perceived QoS and paid price is accounted for in users' preferences. This determines in a decentralized manner users' choices in the sense of a transmission rate selection. Subsequently, we consider the multiple users' medium access to the radio channel and evaluate the performance by means of simulation. The overhead due to collisions and retransmissions, as well as the limited bandwidth, is taken into account so as to see how the achievable rate is affected by users' choices. In this way, we are able to gain understanding at several levels of the behavior of Distributed Coordination Function of IEEE 802.11b, which possibly allows to explore suitable management and pricing strategies for realistic cases.**

I. Introduction

Wireless Local Area Networks (WLANs) based on the IEEE 802.11b protocol [1] are a widespread and consolidated reality. These systems are often found in the form of hot-spots, where a central access point is used as a gateway by a set of mobile terminals. This implementation is especially suitable for the IEEE 802.11b protocol Distributed Coordination Function (DCF), based on Carrier-Sense Multiple Access with Collision Avoidance (CSMA/CA). In this situation, the operating conditions strongly affect the performance of the network [2], [3], thus the need arises for an efficient Radio Resource Management (RRM). The most difficult part in analyzing the multiplexing of the users on the shared radio resource is that the CSMA/CA mechanism of IEEE 802.11b intrinsically does not allow easy and simple evaluations. The impact of collisions and consequent intervals spent by the terminal for backoffs and retransmissions may result in a considerable difference for each terminal between the requested transmission rate and achieved performance.

Intuitively, according to the number of users present in the network, the rate allocated to a specific user can range from an upper bound given by its entire signalling rate to a rate almost equal to zero. The former is guaranteed to be assigned when there is only one user in the network, whereas if more and more users are present, then congestion will cause the traffic to be stuck by a huge amount of collisions.

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At this point also users' preferences have to be considered, as the network management must at least be able to provide users with a *satisfactory* amount of resource. Since the service is intrinsically best effort, there is no guarantee about the service performance, even though users understand when the Quality of Service (QoS) is acceptable or not. How to model Radio Resource Management under these aspects is an open field for research, in which several interesting contributions have been recently presented [4], [5]. In particular, the concept of utility functions and ideas taken from game-theory have been employed to describe how the appreciation of the service depends on tunable parameters, e.g., the transmission data rate of the terminal [6]. It has also been shown that micro-economic concepts can be employed to both explore the effort of maximizing users' utility [7] and price the resource usage in order to achieve an efficient management [8], [9].

Our goal in this study is to integrate the CSMA/CA capacity of an IEEE 802.11 system with the MEDUSA model [10], which is a proposal made by the authors to account for users' choices driven by their appreciation of the service. We study RRM metrics represented by simple functions, like the number of admitted users or the total allocated resource, or by more specific choices from the economic point of view, like total revenue earned by the provider. This part follows almost directly from the evaluation of users' service appreciation. Instead, the contribution presented here aims at investigating the capacity constraint, which is the most difficult part for the study, since no analytical expression can be found in close form.

In more detail, we trace the outcome of packets by considering collisions and backoff intervals of a generalized CSMA/CA Medium Access Control (MAC). The capacity constraint of the model is regulated according to the standard and other parameters describe a simple IEEE 802.11b WLAN hot-spot. The first important contribution is a simulation study on how in such a scenario the rates are affected by the CSMA/CA constraint and which is the relationship between the requested rate and the actually allocated rate.

Secondly, we investigate the role of pricing in determining resource usage. An appropriate price setup is key in achieving a satisfactory revenue, but also in effectively managing the constrained bandwidth. In fact, besides causing revenue generation, pricing the system usage also allows a better coordination and a more efficient utilization. In other words, price tuning can be seen as an implicit Admission Control (AC) mechanism.

Finally, we compare the simulation outcome with preliminary results shown in [11], where a more simplified model of MAC has been used. A comparison can be useful to gain insight on the actual behavior of IEEE 802.11b WLANs.

The work is organized as follows: in Section II we outline the MEDUSA model and discuss its possible applications to the case of RRM for a Wireless LAN. In Section III we investigate more specifically the IEEE 802.11b case and describe the simulator used. Finally, Sections IV and V present the numerical results and the conclusions.

II. The MEDUSA Model

We perform the integration of the perceived QoS and the paid price as factors tuning the users' satisfaction by means of the MEDUSA micro-economic model presented in [10]. Here, if we have N users, for each i between 1 and N an *Acceptance probability* A_i is assigned to the ith user, depending on the utility u_i and the paid price p_i. Both these factors tune the users' satisfaction: the key idea is that they are explicitly merged into a single expression to account for their trade-off.

Several expressions are possible for an appropriate acceptance function. In [10] we proposed the following:

$$A(u_i, p_i) = 1 - e^{-k\cdot(u_i/\psi)^{\mu}\cdot(p_i/\phi)^{-\epsilon}}, \qquad (1)$$

where k, μ, ϵ, ψ, ϕ are appropriate positive constants.

Both u_i and p_i are parameters dependent on the allocation of a generic resource, called r_i, that in the present paper is identified with the transmission rate of the terminal. Henceforth, in this case an allocation is feasible first of all if it lays within a range $[0, \mathcal{M}]$. We take $\mathcal{M}$ as the signalling rate of the terminal, which is regarded also as the maximum transmission rate. Secondly, the total resource allocated to all users can not exceed another threshold $\mathcal{T}$, which is the available resource in the WLAN access point. This imposes the additional constraint $\sum_{i=1}^{N} r_i \mathcal{T}$. Since we want to model here an IEEE 802.11b WLAN, we take $\mathcal{M} = \mathcal{T} = 11$ Mbps, however this choice is not particularly restrictive.

The acceptance probability A_i is used to determine whether users consider the service acceptable; thus, it is possible to evaluate the average number of satisfied users by summing the A_i's. It is also possible to evaluate the amount of resource allocated to satisfied users, or the revenue generated by them. In the following we will assume that unsatisfied users leave the service, therefore every evaluation is implicitly performed on satisfied users only.

The actual value of A_i is indeed a function of r_i, whose shape depends on $u_i = u(r_i)$ and $p_i = p(r_i)$. These functions are not discussed here in detail; however, it is common to adopt simple regularity assumptions for $u_i(\cdot)$ and $p_i(\cdot)$, e.g., being quasi-concave non decreasing functions. It is usual to also impose additional simplifying assumptions, like having upper-limited utilities and elementary pricing strategies, and this can simplify the problem even further. In the following, we will assume that the utilities are sigmoid-shaped, i.e., they satisfy the following expression:

$$u_i(r) = \frac{(r/\kappa_i\mathcal{M})^{\zeta_i}}{1 + (r/\kappa_i\mathcal{M})^{\zeta_i}}. \qquad (2)$$

where $\kappa_i \in [0, 1]$ and $\zeta_i > 1$ are tunable parameters, randomly generated for each user, whose ranges and distributions depend on the scenario. Furthermore, we adopt a linear pricing function, which means that $p(r) = \alpha r$, where α is a positive constant, for simplicity equal for all users.

An immediate way to apply the MEDUSA framework is as follows. Firstly, we let each user to determine its most preferrable transmission rate r_i as $r_i = \arg\max_{r\in[0,\mathcal{T}]} A(u_i(r), p(r))$. Then, we perform a feasibility check, i.e., we control whether the total requested rates exceed the maximum capacity $\mathcal{T}$. If this is the case, we assume that the packets get lost and the rate of the users are decreased. In doing this, we adopt a sequential approach which tries to capture the fact that in a real WLAN users are allocated one at a time.

From an idealized point of view, the CSMA/CA capacity can be represented by the fact that users can always be allocated until a saturation point is reached. If the bandwidth allocation is perfectly elastic, when the new user's request exceeds the available bandwidth the allocation vector is rescaled in order to satisfy the bandwidth constraint. This might lead to a rough evaluation of the capacity, which has been used to derive preliminary results presented in [11]. Even though the qualitative behavior is correctly represented, the main problem in this kind of analysis is that the overhead and the consequent throughput decrease of the IEEE 802.11b MAC can not be taken into account. To this end, we develop in this paper an extension, by means of a more detailed simulator, which is explained in the following section.

It should also be noted that the dynamic allocation changes imply that users might be happy with the initial allocation, but refuse the degradation in the service due to lower r_i. For this reason, after each re-allocation, we re-evaluate the acceptance probability with a conditional approach [12]. We assume that if the users request is r_i, a lower allocation $\rho_i < r_i$ is accepted, conditioned on the fact that r_i is acceptable, with the following probability:

$$A(\rho_i|r_i) = \begin{cases} \frac{A(\rho_i)}{A(r_i)} & \text{if } A(\rho_i) \le A(r_i) \\ 1 & \text{if } A(\rho_i) > A(r_i)\,. \end{cases} \qquad (3)$$

where the first case accounts simply for the basic concept of conditional probability, where the second considers that users will never refuse a service improvement.

The re-evaluation on the $A(\rho_i|r_i)$'s of the users' satisfaction might imply that already allocated users can leave the service, so that a certain amount of resource is freed and could be iteratively re-allocated. However, for the sake of an easy computation the amount of freed resource is taken into account only in future allocations. This does not introduce inconsistencies in the results, even though small oscillations of the curves can be found.

TABLE I

PARAMETERS OF THE MICRO-ECONOMIC MODEL

Parameter	value
ζ	$[2 \div 14]$
κ	$[0.01 \div 0.125]$
ψ	1.0
ϕ	1.0
μ	2.0
ϵ	4.0
$\mathcal{M}$	11 Mbps
$\mathcal{T}$	11 Mbps

III. ANALYSIS OF THE CSMA/CA CAPACITY

To develop the analysis in more depth, we better focus on the actual mechanism of rate reduction. The hypothesis of having an equitable share of resource can be appropriate if we are interested in studying the general trends, but can produce unrealistic results, especially in terms of numerical values. In particular the throughput and all related metrics are highly overestimated, whereas the CSMA/CA MAC protocol of IEEE 802.11b prevents the network from reaching exactly the maximum theoretical limit of $\mathcal{T}$.

To apply the MEDUSA model in a more realistic way, we simulated a CSMA/CA-like MAC with a higher level of detail. We consider a timeline of 10 seconds of transmission, where temporal intervals can be allocated to the users. In this way, we try to capture the scheduling of time slots, where the exchange of signalling and data packets is performed. On this basis, we evaluate transmission of RTS/CTS packets, carrier sensing, collisions and consequent rescheduling of packet transmissions due to exponential backoff.

We assume a Poisson arrival process, where the packets have a fixed size of 8 kb, hence the packet arrival rates are directly derived from the r_i's allocated according to the MEDUSA model. We allocate users sequentially, to save computational complexity. Thus, the data rate achieved by user i is equal to r_i if its own packets do not collide with others allocated previously. If the allocation of a new series of time intervals, corresponding to a new user entering the network, overlaps with already allocated users, our simulator checks for every overlap if it happens within an exposure time corresponding to one eighth of the packet. Note that different values of the packet size and the exposure time have also been tried, showing only small quantitative variations. However, in every case the approach can be adapted to the specific characteristics of a given IEEE 802.11b implementation.

For every overlap of packets, if the transmission starting points are further than the exposure time, the packet with the earlier transmission time is kept, whereas the other one is rescheduled with an exponential backoff. This aims at simulating that the second user has sensed the transmission of the first one and its packet has been rescheduled. Instead, if the overlap occurs within the exposure time a collision arises, and both packets are lost. Thus, the backoff process is initiated for both users.

After the evaluation time of 10 seconds, it is possible to evaluate the rate actually achieved by each user, and to analyze

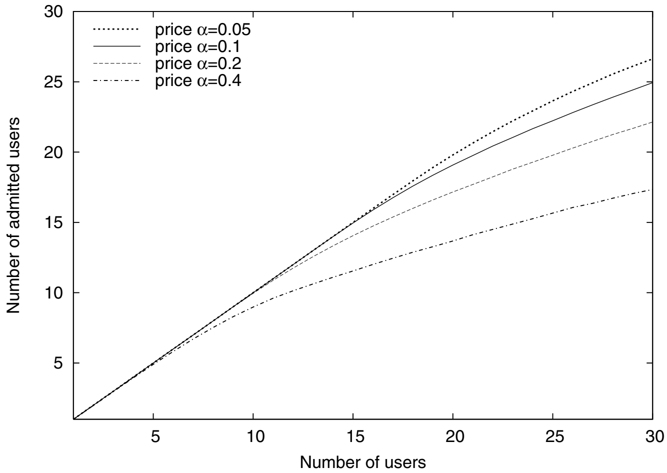

Fig. 1. Number of admitted users as a function of the load

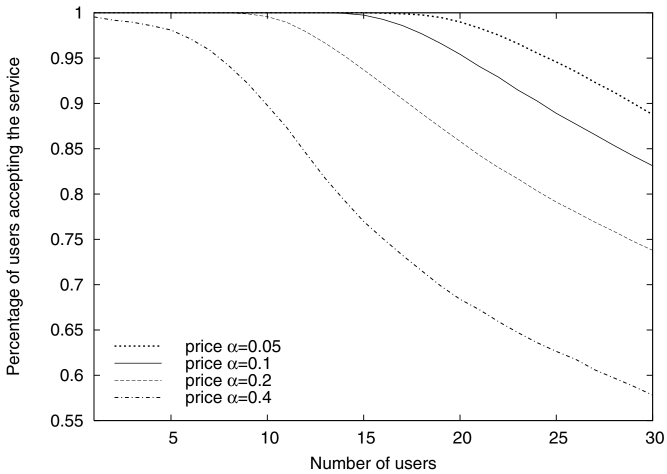

Fig. 2. Admission rate as a function of the load

a posteriori the acceptance of this value. To do so, we perform the dynamic evaluation of users' reaction as explained in the previous section, i.e., by taking the conditional acceptance probability into account. Then, unsatisfied users are removed and another timeline of 10 seconds is considered, where only the remaining users are allocated. This approach might be heavy from the computational point of view, nevertheless it is also capable to obtain more realistic values for the rate allocation according to the IEEE 802.11 MAC.

IV. RESULTS

All the results shown in the following concern the more realistic CSMA/CA simulation approach discussed in Section III. For the sake of comparison, interested readers can refer to [11] where similar investigations have been performed for the simplified approach briefly outlined in Section II. A short commentary of this comparison is also presented at the end of this section.

The simulation scenario consists of N potential users connected to an AP to simulate the WLAN hot-spot. We assume that all users are covered by the same access point and multi-hop capability is not present. Table I shows the parameters of the MEDUSA model to fully specify the formulae presented

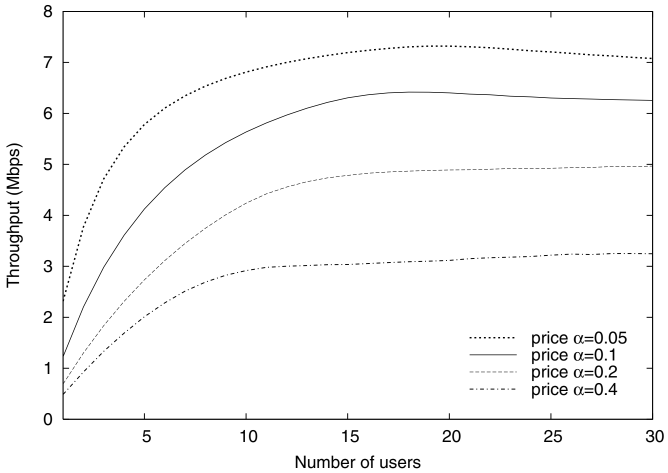

Fig. 3. Network throughput as a function of the load

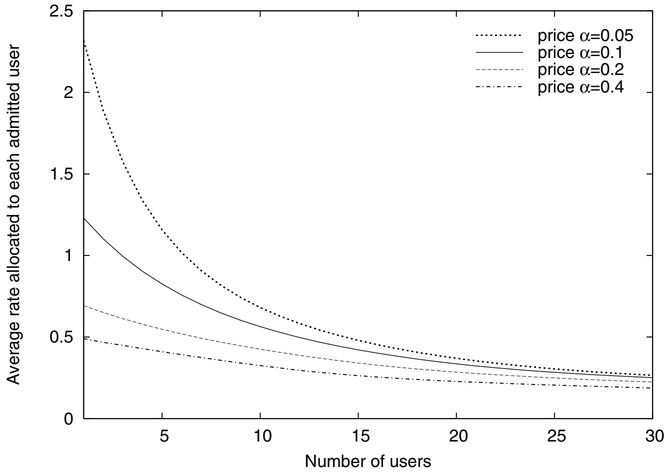

Fig. 4. Average rate per user as a function of the load

in Section II. In these results, we always trace N on the x-axis, i.e., we investigate how the performance is influenced by variations in the number of potential users. Also, we consider different values of the price coefficient α to study the effect of pricing.

Figure 1 shows the number of admitted users, i.e., the number of users who accept the service conditions vs. the total number of users in the system. The acceptance decreases as the price increases, but still we can observe an increasing behavior for all curves, as more users are present. This implies that the IEEE 802.11b MAC protocol is able to allocate users in an elastic manner. Approximately, we observe a linear increase common to all price curves, then when the capacity is saturated the slope decreases but the increase remains more or less linear. The larger the price, the further the number of users at which the slope change happens, and also the lower the final slope. The acceptance rate evaluation is better emphasized in Figure 2, where the values of Figure 1 are represented as a fraction of the potential users.

Figure 3 represents the total amount of allocated resource as a function of the load. This can be seen as a throughput estimate, since the CSMA/CA capacity is actually taken into account in neglecting collided packets or overhead in the sum

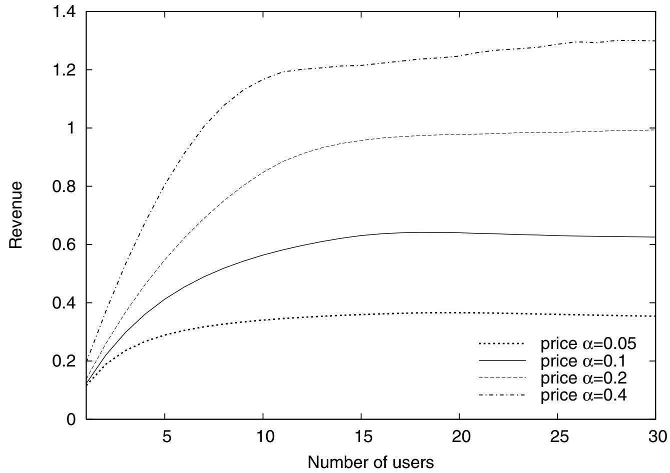

Fig. 5. Total revenue as a function of the load

of the r_i's. It is highlighted that the throughput increases linearly at first in the number of users, then it saturates to a value which is decreasing as the price increase. It is also visible that the throughput saturation value can be significantly lower when the price is high, and this is due not only to the presence of network protocol overhead, but also to the fact that rate decreases implied by protocol inefficiencies cause the unsatisfaction of more users.

In Figure 4 we represent the same situation but considering the ratio to the number of admitted users. With respect to Figure 3, here it is shown that the average allocated rate tends to be more or less similar when the number of users is sufficiently large. However, from the previous results it is also clear that the difference is in the number of satisfied users vs. the total allocated resource, i.e., when the price is high we allocate approximately the same rate to the users, but fewer users accept and then the throughput is lower.

Finally, we consider the revenue in Figure 5, whose behavior follows the throughput since the price is linear. However, the trend of the saturation value vs. the price choice is the opposite of Figure 3. Since doubling the price does not mean a halved throughput, the price increase improves the network management from the point of view of achieving high revenues. This means that the price choice is not trivial, and must be accurately checked according to the provider's objective. In fact, contrasting results can be found if the network management objective is either high resource allocation or high revenue. In general, both goals present pros and cons, and cutting the trade-off is needed, which is an issue that can be developed in future research.

As a general remark, we observe that the results are qualitatively similar to the ones shown in [11]. Thus, we infer that for a simple qualitative analysis a preliminary investigation, where the inherent MAC characteristics are neglected, is sufficient. On the other hand, for a more detailed analysis and also for a realistic numerical evaluation, the specific MAC protocol must be taken into account in some way. However, a trade-off between these two approaches is currently under investigation, to seek if it is possible to find a technique that combines numerical accuracy and fast evaluation of the results.

V. Conclusions

This paper investigates a WLAN hot-spot regulated by the CSMA/CA capacity constraint, as in the IEEE 802.11b DCF standard. We applied to this scenario a micro-economic model where users' choices are tuned by means of two knobs: utility and price. From our analysis, it emerges that both the price setting and the number of potential users in the network have a strong impact, and they are also heavily related and imply non-trivial effects in particular on the throughput and on the total earned revenue.

Indeed, the pricing policy plays a key role for the correct evaluation of the system performance, since it can tune the number of users accepting the provided service, but the users' sensitivity to this phenomenon can be very high. Also the number of users is key in achieving efficient performance, but the CSMA/CA-based multiple access exhibits good behavior in multiplexing users' requests in an elastic manner. However, many points of trade-off have been identified and the optimized design choices on this matter can be subject of future research.

More in general, there are inter-dependencies between economic parameters and protocol efficiency, which can be studied through our model. A possible application is then useful not only for measurement purposes, but also to search for possible protocol improvements which can be achieved by exploiting economic knowledge.

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