Micro-economic Strategies for the Radio Resource Management of Heterogeneous Access Techniques

Leonardo Badia, Diego Guerra†, Michele Zorzi*†*

* Department of Engineering, University of Ferrara, Ferrara, Italy
† Department of Information Engineering, University of Padova, Padova, Italy
{lbadia,zorzi}@ing.unife.it, guerra@dei.unipd.it

Abstract— **We investigate Radio Resource Management techniques for heterogeneous networks, where also attention is paid to economic aspects such as users' utility and service pricing. Our main focus is on a scenario where different Radio Access capabilities are coexisting, so that there are several alternatives for the resource allocation. Thus, we propose a comparison, both from technical and economic point of view, of strategies with simple prioritization and with awareness of users' reaction to QoS. We show that this latter class is able to heavily improve the network management, and this is utilized to derive general insight and propose further improvements of the allocation strategies.**

Keywords: Radio Resource Management, Allocation Techniques, Heterogeneous Networks, Economic models, Utility functions.

1. INTRODUCTION

Wireless Communication Systems are evolving toward the availability of different coexisting radio access techniques, so that future networks will be able to provide users with strongly differentiated services and data rates. Harmonization and cooperation of different radio access techniques is henceforth sought, in order to improve the efficiency of the management [1, 2]. It is commonly thought that the best way to achieve performance improvement of current networks is through the integration of heterogenous radio resources.

In this paper, we regard the efficiency of the allocation in a heterogeneous wireless network from two points of view: QoS supplied to the users [3] and global network management of the entire network also in economic terms (i.e., market share or generated revenue) [4]. To approach these points, utility functions can be used as general means to describe Quality of Service (QoS) [5]. Furthermore, we argue that it is necessary to include also the issue of pricing in our analysis, since the reaction of users to the quality vs. price trade-off impact on the business management of the network, which has to be sustained by adequate revenues. In fact, the global business of the network has to compensate the deployment and management expenses.

Thus, we consider a joint technical and economic model to evaluate the Radio Resource Management (RRM), which has been presented in [6] and is motivated by the above rationale. In particular, the model is employed to determine the users' reaction to QoS and pricing and this is applied to a scenario with multiple medium access technologies, which is the main focus of our investigation. In particular, we investigate the benefits achieved by the network provider in supporting a plurality of access techniques, and at the same time we argue that the gain is larger if the allocation strategy is able to account not only for simple technical considerations, but also for economic parameters, in particular for users satisfaction. For this reason we compare different allocation strategies, and we show that significant gains are obtained by accounting for the users' service perception.

The guideline of our investigation is as follows: first of all, we discuss the introduction of utility functions [7] and we extend this analysis to a model of users' behavior, where also the pricing is added to the service evaluation. In this way, the analysis of allocation techniques in heterogeneous networks is faced by means of a joint economic/technical model [8]. In particular, the model considers an evaluation of the users service appreciation described through a value called acceptance probability A_i, which can be seen as the probability of a given user i of being *satisfied* with the current utility level and price paid. Secondly, we compare different allocation strategies, by distinguishing in particular among two main classes, where the allocation is either performed with a fixed priority of access techniques or this prioritization is made adaptive by looking at the utility generated by the allocation [9]. This latter category of policies will be shown to heavily improve the allocation, since it presents both qualitative and quantitative improvements in the metrics of interest.

In particular, our investigation will discuss the following evaluation metrics of the RRM efficiency. First of all, we investigate the network capacity in terms of the number of satisfied users. This quantity is related on how the allocable resource allowed by the network capacity is shared among the users in an efficient way. Note that only *satisfied* users are worth, since it is reasonable to assume that the resource allocated in an unsatisfactory manner is wasted, and the users under a decent QoS level will leave the network in the long run.

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This can be also quantitatively measured by evaluating the total utility of the admitted users, i.e. a weighted sum of the utility times the acceptance probabilities of each user. Finally, we might directly evaluate the economic performance by looking at the total revenue, where again only satisfied users are considered. This is another weighted sum, but instead of the utility we consider the price paid by every user.

A detailed outline of the paper is as follows: in Section 2 we will discuss the resource allocation and its impact on users' behavior, which is described by means of a joint economic/technical model which explicitly considers the trade-off between utility and price. This model is also extended to the case where different resources are present. In Section 3 we compare possible strategies and investigate the different results obtained. Finally, Section 4 concludes the work.

2. QoS vs. PRICE MODEL

Utility functions are mathematical instruments introduced in micro-economics [10] to evaluate the goodness of a particular allocation of a resource, represented with a generic non-negative parameter r. In the following section, this analysis will be extended to a multi-dimensional allocation. For the RRM sake, r can be thought as the transmission rate of a data transmission. In particular, we focus on the assignment of the resource among a network with N users, which can be described through an allocation vector $\mathbf{r} = (r_1, r_2, \ldots, r_N)$, where r_i is the allocation value for user i.

If each user is associated with a utility function $u_i(r)$ describing the QoS perceived by user i depending on the allocated resource r, the vector $\mathbf{u} = (u_1(r_1), u_2(r_2), \ldots, u_N(r_N))$ translates the allocation $\mathbf{r}$ into levels of QoS. The $u_i(\cdot)$'s are different for each user, as they depend on subjective parameters, which for the RRM case can be, e.g., the kind of terminal or service enjoyed. However, in general every $u_i(\cdot)$ is a non-decreasing function of the allocation, with an upper limit that can be thought as due to technological constraints.

To extend this view of the allocation centered on the perceived QoS solely, we add also a *pricing function*, $p(r)$ to evaluate the price paid by the users. We argue, in fact, that the pricing issue is also strongly impacting on users' service appreciation [8]. In other words, too high a price can drive customers away; however, as we will see in the following, too low a price can also be inefficient, since the network resources are requested by more users than the system capacity can allocate, thus resulting in network congestion.

In the present paper the function $p(r)$ is the same for all users. This hypothesis is adopted for simplicity. However, it is also possible to assume that few *pricing classes* are co-existing in the network [11]; the extension of the analysis to this case is straightforward. The pricing is a non-decreasing function of the assigned resource, and it concurs together with the utility in determining users' choices. In fact, the service acceptance of user i, determined by the trade-off between perceived QoS and price paid for it, is reflected by an *Acceptance value* A_i, which depends on $u_i = u_i(r_i)$ and $p_i = p(r_i)$.

We interpret A_i as the probability that the ith user is satisfied with the service condition and therefore sticks to the network. As a consequence, we will consider a network where N is the number of *candidate* users and we will evaluate the network performance for the satisfied users only, since it is assumed that the contributions to the total utility, or to the revenues, coming from unsatisfied users will drop to zero after a short period.

Several expression are possible to define A_i, which must be a decreasing function of the price and an increasing function of the utility. In the present work we adopt the following choices: 1) $A_i = A(u_i, p_i)$, i.e., the service acceptance value is determined identically for all users as a function of u_i and p_i only (this can be extended again by adopting a class-based approach); 2) All utilities are normalized, i.e., the highest QoS that can be perceived by a user corresponds to the value 1 on the utility scale; 3) The price, which is not upper-limited, is normalized to the value considered fair by 10% of the users; 4) With the above conventions, we take

$$A(u, p) = 1 - \exp\{-(\log 0.9)(u^2/p^4)\}. \qquad (1)$$

Equation (1) is motivated by the fact that in this way condition 3) is also automatically verified, as well as the monotonicity conditions with respect to u and p. The other choices of parameters can be replaced with different ones, in particular the exponents 2 and 4 for u and p, respectively, capture the economic sensitivity of the acceptance value on variations of utility and price. With this choice, every user in the network is moderately sensitive to utility variations and considerably sensitive to price variations.

The above framework can be used to evaluate different quantities related to the efficiency of the RRM. In particular, we adopt these performance metrics:

- **Number of satisfied users**. This is calculated as: $S = \sum_{i=1}^{N} A_i$. This quantity is related on how the allocable resource allowed by the network capacity is shared among the users, since in general S depends on the trade-off between utility and price.
- **Total utility of the admitted users**. This is a weighted sum of the utility times the acceptance probabilities of each user, i.e.: $U = \sum_{i=1}^{N}(A_i u_i)$.
- **Total revenue**. This is another weighted sum, but instead of the utility we consider the price paid by every user, which means: $R = \sum_{i=1}^{N}(A_i p_i)$. Note that in this case the price has a twofold effect, since it appears twice in the expression (it is also inside A_i). Thus, a price increase has a non trivial effect

on R since every single contribution $A_i p_i$ on the one hand increases in p_i but on the other hand it decreases in A_i.

This model needs to be extended in order to account for the coexistence of multiple access techniques in the network under exam. A possibility to do so is to translate the quantity r to a multi-dimensional space. In other words, we assume to have ν different access techniques. The utility functions which describe the QoS coming from the assignment of a given amount of resource on a given access techniques are different. For the sake of simplicity, we consider to have randomly generated utilities, thus their parameters will be, for every user, a i.i.d. realization of a stochastic process. Moreover, we assume that only one connection at a time is possible, i.e., multiple access diversity is not taken into account. Finally, we consider that all the techniques are available for each terminal (this is not restrictive since it might be thought that a terminal without connectivity for a given network access technique has simply utility identically equal to 0).

Thus, the resource manager has two degrees of freedom in determining the allocation for a given user: first of all, it has to decide on which kind of resource the user will be allocated, i.e., which kind of access technique will be used. Once this is determined, the allocation of the quantity r_i is determined according to the capacity constraints of this particular access technique. In this work we focus in particular on the first part of this selection process, by identifying and comparing different techniques for the selection of the access technique where to connect a given user. For what concerns the second part, we assume that the resource manager adopts a general mechanism which operates as follows. First of all, a tunable parameter $\beta > 0$ is selected. Then, each user is provided with an assignment which has to be both feasible with the capacity constraint and guarantees a marginal utility increase equal to β. In other words, the amount of resource to allocate to user i is such that

$$r_i = \max(r_{i0}, r_{i1}) \quad (2)$$

where r_{i0} is the maximum available amount of resource which is feasible to allocate, and

$$r_{i1} = \max\{r : u_i'(r) \geq \beta\}. \quad (3)$$

This implies that each user is provided with the maximum feasible amount of resource that marginally increases the utility of a factor β. This allows a tunable allocation: the larger β, the lower the average allocation, since the utilities are increasing functions. This behavior is better explained by Fig.1.

For the sake of simplicity, in the present paper we assume that the feasibility constraint to represent the (single or multiple) network capacity is a hard capacity constraint [12]. This means that a fixed amount of resource T_j is available for the generic jth access technique, so that the users can exploit a given access technique until it has resource available. Formally, the capacity constraint can be expressed as

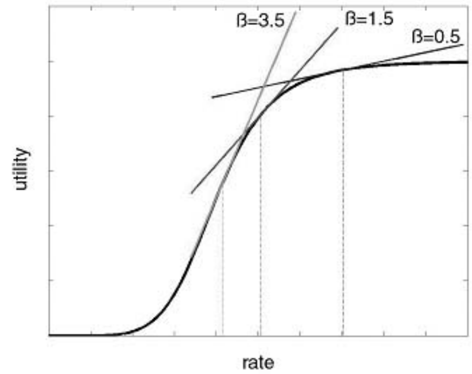

Fig. 1. Tunable allocation by means of the first derivative of the utility

$$\sum_{i=1}^{N} r_i^j \leq T_j \ , \quad (4)$$

where r_i^j indicates the resource allocated for user i on the access technique j. In other words, every new allocation decreases the available capacity in an additive manner, i.e., the network can be seen as a generalized TDMA or FDMA network. Extensions to more complicated interference-limited capacity [13] are still possible, without substantially changing the results.

In order to fully specify the model, these assumptions are required. The utilities are represented with the following parametric sigmoid function:

$$u_i(r) \triangleq \frac{(r/K_i)^{\zeta_i}}{1 + (r/K_i)^{\zeta_i}} \ , \quad (5)$$

whose parameters K_i and ζ_i are randomly chosen with uniform distribution in the intervals $[0.1, 0.5]$ and $[2, 20]$ respectively. The price instead is a linear function of the allocated resource, i.e., $p(r) = kr$, where the coefficient k is one of the key parameters of the overall system dimensioning and will be considered as the independent variable in our following evaluations.

Thus, what is still left unspecified is only the choice of the radio access technique selected by every user, which is the main focus of the investigation of the present paper and will be discussed during the next section.

3. STRATEGIES FOR THE CHOICE OF THE RADIO ACCESS TECHNIQUE

We focus on a network where users are randomly spread around several Access Points (APs). For the sake of simplicity, all APs allow connection with multiple radio access techniques. In the following simulation results we consider 19 APs, $N = 320$ users and $\nu = 5$ different

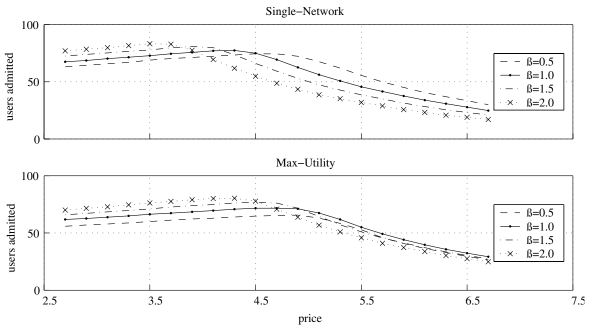

Fig. 2. Comparison between Single-network and Max-utility: number of admitted users for 320 users, as a function of the price

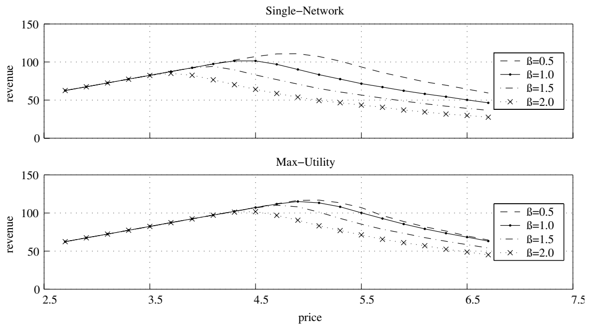

Fig. 3. Comparison between Single-network and Max-utility: provider revenue for 320 users, as a function of the price

access techniques. The total network capacity is C, normalized to 1, and every user might be provided at most with the value r_{max}, equal to $C/25$, as transmission rate.

The first strategy introduced in this paper is a straightforward allocation which arbitrarily prioritizes among the available connections, with an order decided *a priori*. In the end, this access selection strategy is equivalent to the allocation on a single network, since there is no optimization of the availability of different access techniques at the same time. In other words, it is like having only a network at a time. For this reason, the allocation procedure is called *Single-network*. It works in the following way: assume that the available access techniques are numbered from 1 to ν. This can be done even randomly. Then, users are allocated on network 1 as long as the available capacity on network 1 is enough. When it is saturated, the resource allocator starts to use the access technique number 2 and so on.

As an alternative, we investigate here another strategy, called in the following *Max-utility*, where a similar sequential allocation of users is performed, but this time the selection is made according to the utility coming from the allocation. The access technique which guarantees the highest utility to the user is selected, provided that there is enough resource available on it.

Note that this is still a greedy strategy and henceforth no optimality is guaranteed. Moreover, there is plenty of different strategies that can be adopted instead of Max-utility, offering similar results. Our goal here is only to compare these two strategies and show that the awareness

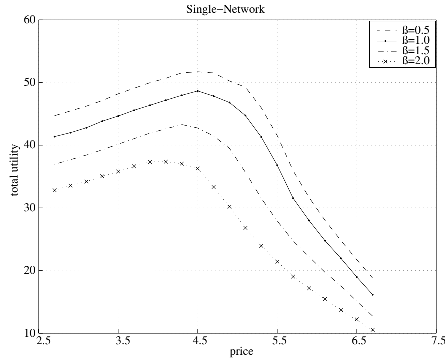

Fig. 4. Single-network: total network utility versus price (320 users)

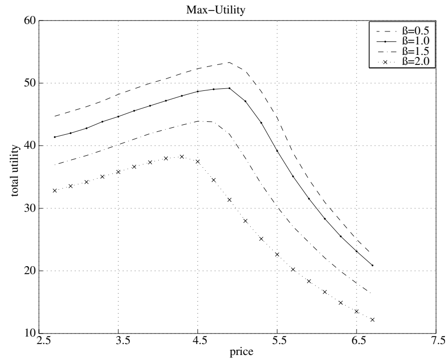

Fig. 5. Max-utility: total network utility versus price (320 users)

about users' service perception, obtained with an easy selection rule, allows to highly increase the performance. Later on in this section, we will briefly discuss possibility of further improvements obtained by allowing speculations on the allocation strategy, i.e., selection of the access technique based on the estimate of users appreciation made with the same model discussed in Section 2.

Consider Figs. 2 and 3. Here, comparative results are presented for the two aforementioned class of strategies, i.e., the Single-network and the Max-utility classes. In particular, we focus on two metrics, i.e., the total revenue and the number of admitted users. For each of the two strategies we consider four possible values of β, which is the marginal utility applied to the sigmoid-shaped (with randomly generated parameters, different for each user) utilities. In general, the higher β, the higher the rate allocation proposed to every user. The price is a linear function of the allocated resource, and the unit price is the coefficient plotted on the x-axis of Figs. 2 and 3.

It is clearly visible that the allocation obtained with the utility-aware strategies is more efficient. In particular, not only the Max-utility strategies obtain higher values with respect to their corresponding counterparts of the Single-network strategies, but also the differences between the four different choices of β are reduced. This is a consequence of the fact that a utility-aware allocation is more appreciated by the users and therefore is less sensitive on the average quantity of allocated resource, since in the end the QoS is increased anyway.

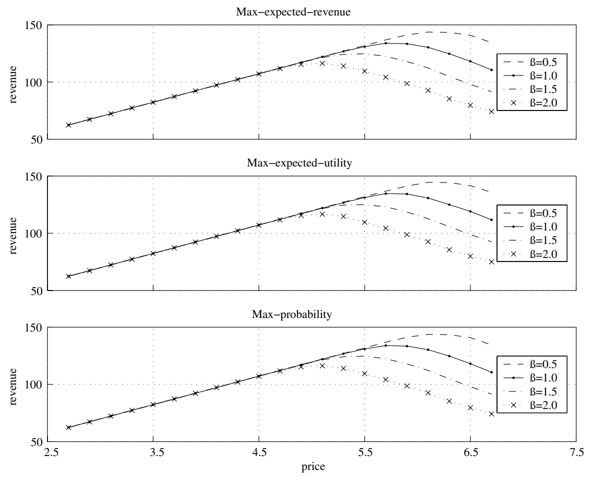

Fig. 6. Speculative allocations: total revenue for 320 users, as a function of the price

Finally, also the utility is improved by the Max-utility allocations. In fact, the performance improvement can be seen as a consequence of the larger overall network utility obtained by the Max-utility policy, as it is visible by comparing Figs. 4 and 5, which show the total utility for the two considered allocation strategies.

The increase of the efficiency due to the Max-utility strategy can be pushed further, since the simple prioritization according to the perceived utility does not mean that the user fully appreciate it. For example, it might happen that the access technique guaranteeing the highest quality is also the most expensive, whereas the microeconomic model discussed previously also aims at taking the price into consideration. For this reason a good idea could be to perform estimation not only based on the link quality of every access technique, but also, employing the same economic models introduced in Section 2, on how this different quality will be appreciated by the users. Such estimations lead to the formulation of different *Speculative allocation strategies*, where the speculation is in the fact that the awareness on economic parameters is used also to prioritize the access techniques.

By adopting the same classification made in Section 2, the following quantities can be used for the speculation: probability that the user will accept the service, expected contribution to the total network utility, expected contribution to the total revenue. These parameters lead to different allocation strategies, which however in our simplified scenario perform very similarly. The measurement related to the total revenue obtained with these policies is reported in Fig. 6. Here, preliminary results on the total achievable revenue by maximizing the average revenue, the average utility, the average number of users, respectively, are plotted. It is emphasized that the improvement obtained by means of these policies is even larger than for the Max-utility strategy. Thus, these policies appear as very promising in order to improve the effectiveness of Radio Resource Allocation in heterogeneous scenarios.

4. CONCLUSIONS

In this paper we have explored the capabilities of economic models to describe the Radio Resource Management for heterogeneous networks and the possibilities of improvement deriving by such a description.

The awareness of users' utility is able to achieve better performance for the overall network allocation. In particular, this is emphasized by the considerations related to utility vs. price trade-off. This means that in a realistic allocation scenario it is key to accurately estimate the users' service appreciation and also to take it into account with appropriate models in order to evaluate the impact of QoS and pricing on the users' service acceptance.

In particular, we showed that a yet simple strategy like imposing a prioritization on the available access technique based on the perceived utility allows to improve the performance. An even larger gain can be obtained by using the evaluation of the users' acceptance in a more elaborate way, i.e., by allowing speculations on the estimate of the service acceptance instead of the pure measure of the utility. This last study seems very effective and it is therefore a possible subject of future research.

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