An Economic Model for the Radio Resource Management in Multimedia Wireless Systems

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Abstract

In this paper, we study the connection between Radio Resource Management and economic parameters, whose application in multimedia communication system is a challenging task. In fact, a real network provider has to consider other parameters, besides the common goals of Radio Resource Management like throughput maximisation or meeting constraints connected with the Quality of Service. In particular, when the financial needs of the provider and the reaction of the users to prices are taken into account, economics have to be introduced in the analysis. We intend to study multimedia communication systems by including well-known economic models and reasonable considerations in the usual Radio Resource Allocation scenario. To do this, we present a model of users' satisfaction, which considers the effects of both users' request and price paid. In this way it is possible to investigate the relationship between the Radio Resource Allocation and the provider revenue. Other conclusions can be derived as well, e.g., for the pricing strategy planning or the network dimensioning. Thus, we give analytical insight and numerical results which highlight that the network management is heavily affected by the economic scenario.

1 Introduction

During recent years, a huge development of new services and also several novel business models have been seen in cellular telephony. While Radio Resource Management (RRM) is key to high performance of communication systems, many economic factors also have a strong impact.

The Quality of Service (QoS) concept is often studied in connection with its economic meaning, where tariffs and provider revenue are considered important as well as other parameters of more technical nature [1]. At the same time, several researchers have adopted micro-economical concepts to analyse next generation communication systems [2] [3] [4] [5].

However, in these descriptions, non-technical parameters as user satisfaction or pricing are considered only from the users' point-of-view, e.g. in decentralised approaches. The role of the provider is neglected, or the provider is merely considered to act as an arbitrator that guarantees the welfare of the users. In fact, these studies usually apply game-theoretical concepts, like utility function [6], to optimise or simply improve the usage of the Radio Resource. In certain cases a connection with *virtual* prices is also made [7]. However, nothing is said about the *real* pricing policy of the operator, how the users react to it, and which could be the best strategy for the provider.

We think that the increasing influence of economics on communication systems makes it necessary to extend the analysis also to this field. The first reason is that a concrete provider needs to be able to estimate the revenue that can be generated by different RRM strategies. To decide which services should be implemented, to dimension the network capacity and to correctly share the bandwidth among the users, the economic income has to be measured in some way. In general, the existence of the network itself is guaranteed only as long as there is an adequate revenue for the operator.

Then, in a centralised network the provider can act directly to pursue its goal, i.e., to increase its revenue. However, users' reactions to the tariff are an important factor as well. Real world users are far from being indifferent to prices. Thus, their satisfaction is determined by both the quality of the connection and the price paid for it. If the role of pricing on users' satisfaction is neglected, the conclusions can be misleading.

Henceforth, in this work we propose an analysis of economic aspects, by studying the users' satisfaction in multimedia communication systems. The QoS is modeled with the well-known concept of utility functions, that correctly model the soft tunability of the perceived quality in modern networks. The same model is used also for the price, that is indeed a continuous quantity [8] that could be adjusted by the provider, according to a pricing policy known to the users and in general defined a priori.

In the sequel, we apply the framework to the rate allocation issue, in which a usage-based pricing policy and a class of allocation policies are evaluated. Several useful insight are given for real cases of RRM. In particular, the system capacity is discussed in detail, as our model shows different behaviours, also under the economic aspect, for systems characterised by *hard* or *soft* capacity, respectively.

The work is organised as follows: in Section 2 we discuss the basic properties of utility function and price function and present the theoretical framework to depict the users' satisfaction. In Section 3 we present different kinds of networks and define a simple case study to apply our model. In Section 4 we show simulation results that give several insights about the systems under exam. Finally in Section 5 we conclude the work.

2 Model for the Behaviour of Network Users

We present a model developed from the economic concept of utility function, widely used to depict the QoS perceived by the users of a wireless network. Even though this concept is derived from micro-economics [9], it is often adopted in the recent literature [10] to mathematically depict the QoS degree perceived by the users. There are several possibilities to define a numerical representation of QoS: one example of such kind could be the 5-level mean-opinion-score (MOS) [11], that directly considers the perception of the service and numerically grades the QoS via subjective testing. Different cases of resource assignment are considered and the grades can be easily transformed into a function by means of interpolation between the samples.

Strategies to derive utility functions are not investigated here in detail. We simply assume that a utility function $u(g)$ maps some quality-related parameter g, $0 \leq g < \infty$, onto an interval of real numbers, discrete or continuous. Note that, in the case of RRM, g represents the resource of the network given to the users, and could be one- or multi-dimensional.

Since utilities map the perceived quality, they are increasing functions of the g-parameters, i.e., it is assumed that the greater the resource allocated to a user, the higher its satisfaction. This implies the following requirements on the derivative of the function $u(g)$:

$$\frac{\mathrm{d}u(g)}{\mathrm{d}g} \geq 0\,, \tag{1}$$

$$\lim_{g\to\infty} \frac{\mathrm{d}u(g)}{\mathrm{d}g} = 0\,. \tag{2}$$

Equation (2) is known in economics as the law of diminishing marginal utilities. This reflects the phenomenon according to which the improvement of the QoS is vanishing when an already high grade of satisfaction has been reached. That is a realistic assumption for general cases.

Even though in this work we focus on rate assignment, we develop several considerations that can easily be translated to other kinds of RRM without loss of generality. For this reason g will be identified in the following with the assigned rate. Note that in the case of bandwidth management, technological limits do not allow channel assignments larger than a given threshold, depending essentially on the kind of service and the type of terminal. For this reason in the following we will use:

$$\lim_{g\to\infty} u(g) = l \tag{3}$$

with constant l, that is a stronger condition than Eq. (2). Equation (3) reflects the fact that there is an upper bound to the perception of the QoS for every kind of service. Equivalently, this Equation reflects the human insensitivity to the quality improvement beyond a certain limit.

There is also a maximum value for g, called in the next g_{max}, due to technological constraints. Hence, we will consider assignment of the resource only in the range $0 \leq g \leq g_{max}$. It is reasonable to assume that in practical cases g_{max} supplies a utility close to l. This is equivalent to considering only users able to achieve satisfactory utilities for large g. Let the minimum achievable utility:

$$u_0 \triangleq \min_{g\in[0,g_{max}]} u(g) \tag{4}$$

be the utility of not receiving service, i.e., $u_0 = u(0)$. In the following we will assume $u_0 = 0$. Note that both these conditions can be related to Admission Control (AC). In practice, we are assuming that the AC is actually blocking the users with low values of the utility even for g close to g_{max} and this decision is error-free, i.e., there are no admission errors that cause call dropping or degradation of the service of already connected users. In these cases the utility could go below $u(0)$, being an interruption of the service more annoying than a block in admission. However, in this work the Admission Control is limited to the observation that users are not allocated beyond the system capacity and that users which receive an assignment of rate equal to 0 can be considered blocked. In spite of this, there is no re-negotiation of already allocated users nor a conservative blocking of users which can be considered harmful for the system.

Moreover, a utility function is often also supposed to have certain properties of regularity, which usually include continuous differentiability, at least piece-wise. In particular, when this is verified for every value of g, we speak of *elastic traffic* [12]. Note that this property applied to (2) and (3) implies concavity of $u(g)$ at least for g greater than a given value, i.e.:

$$\exists g_c \,:\, u''(g) < 0\,, \quad \forall g \geq g_c \tag{5}$$

The exact behaviour of the utility depends on the kind of multimedia traffic we are assigning to the users. For the simplest kind of service, e.g., GSM voice-like calls, it is commonly assumed that the quality degree of the service is on/off, i.e., $u(g)$ is bound to have only two values, which mean complete satisfaction or dissatisfaction for the user. This is not true when next-generation services like data transfer or audio/video streaming are taken into account. These services can be considered elastic traffic, since the services themselves allow different degrees of perceived quality according to the assigned rate, with a soft degradation from the best possible choice to the minimum acceptable quality. Therefore, we consider continuous functions to model the utility for the users.

One of the goals of RRM is to achieve a good users' welfare, considered as an aggregate of their utilities, subject to feasibility constraints. In the case of rate allocation, the main constraint is the limited capacity of the network. However, it seems unrealistic to measure only the welfare without taking into account the role of pricing. The first reason is that the operator will not provide the service if the revenue coming from the users is insufficient. On the other hand, the perception of the service for the users is not always the same if the price is changed: in practice, users are satisfied with the service if both quality and price paid are considered acceptable.

We propose to take this effect into account by defining an *acceptance probability* for every user that requests service. Note that this concept was not strictly necessary for the GSM-like services, in which the QoS can be assumed equal for each admitted users and the price fixed a priori (so that the QoS metrics are usually assumed to be the probability of not achieving the desired Signal-to-Interference Ratio or having the connection refused by the Admission Controller).

We can mathematically model it by considering a utility function $u(g)$, as previously defined, to represent the QoS. The price could also be represented by a function $p(g)$ (in general, dependent of the rate). The price function is in several aspects similar to the utility, for example, it is reasonable to require a condition like Equation (2), i.e.:

$$\frac{\mathrm{d}p(g)}{\mathrm{d}g} \quad \geq \quad 0\,. \tag{6}$$

However, the price is in general not upper-limited.

Let us assign to each user an acceptance probability $A(u, p)$, for which we emphasise the dependence on the QoS (through the utility u) and the paid price p. In fact, this probability has to increase for increasing utility and decreasing price. In more detail

$A(u,p)$ should satisfy:

$$\frac{\partial A}{\partial u} \geq 0\,, \qquad\qquad \frac{\partial A}{\partial p} \leq 0 \tag{7}$$

$$\forall p > 0\,,\ \lim_{u\to 0} A(u,p) = 0\,, \quad \lim_{u\to\infty} A(u,p) = 1 \tag{8}$$

$$\forall u > 0\,,\ \lim_{p\to 0} A(u,p) = 1\,, \quad \lim_{p\to\infty} A(u,p) = 0 \tag{9}$$

where the second part of relationship (8) should be intended as more due to the duality between utility and price, than as in a practical sense, because an infinite utility is not reachable, see Eq. (3). The values of $A(0,0)$ and $A(\infty,\infty)$ can be arbitrarily chosen in $[0,1]$, as the former is the acceptance probability of a blocked user (that is not admitted, regardless of its value of A), whereas the latter represents a case that never occurs in practical systems, due to limited utility. A choice that can assure the validity of conditions (8) and (9) is:

$$A(u,p) \triangleq 1 - e^{-C\cdot u^{\mu}\cdot p^{-\epsilon}} \tag{10}$$

with C, μ, ϵ, being appropriate positive constants.

The choice of this particular function is related to the Cobb-Douglas demand curves [9], that are widely used in economics. If we consider a high number of users in the system, each of them with a very low probability to have access to the system (C close to 0), it is then true that A tends to the demand for the access, i.e.,

$$A(p) \sim d(p) \propto p^{-\epsilon} \quad \text{for given } u,$$
$$A(u) \sim d(u) \propto u^{\mu} \quad \text{for given } p.$$

However, the conclusions we obtain are quite general and do not depend on this particular choice, they are valid for every function that satisfies Eqs. (7)–(9).

With the probability A we can model the behaviour of users in a *centralised* resource assignment scheme in which the only choice left to the users is whether they want to accept the service or not. The revenue is determined as:

$$R = \sum_{i=1}^{N} p_i\, A(u_i, p_i), \tag{11}$$

where the users are considered to be numbered from 1 to N and their relative utility and price to be u_i and p_i respectively.

If the system is centralised and the goal of the provider is the revenue maximisation, we can formulate this task as an optimisation problem:

$$\begin{aligned} \max \quad & R \\ \text{s.t.} \quad & \text{capacity constraints} \end{aligned}$$

The constraints can be defined differently, according to the characterisation of the system capacity. Basically, in the following we will study and compare the cases of *hard* or *soft* capacity, that apply to TDMA- (or FDMA-) like and CDMA-like systems, respectively. However, for both situations the maximisation of the revenue in a constrained case depends on the users' demand. In case of high demand, according to optimisation theory, the maximum for the revenue is obtained on the edge of the constraint. In this case, there are differences between the optimal solutions, due to the different kinds of constraint. For the sake of simplicity, we will study these behaviours by means of simulations in the following Section.

3 Strategies of Rate Allocation and pricing

We consider a centralised and greedy rate assignment strategy, in which the resource manager knows the relation $g \rightarrow u_i(g)$ for every user i. By exploiting this information, the provider tries to choose a value for the rate g that might satisfy the user, being at the same time respectful of the limited amount of bandwidth that can be allocated. This last constraint depends on the kind of capacity, i.e. hard or soft, in the system under exam. After rate assignment, the user can decide whether or not to accept the assigned value, according to the acceptance probability previously defined.

In more detail, the utilities are modelled as sigmoid curves, since they are well-known functions often used to describe QoS perception [4] [12]. We consider the following analytic expression for these curves:

$$u(g) \triangleq \frac{(g/K)^{\zeta}}{1+(g/K)^{\zeta}}, \tag{12}$$

where $\zeta \geq 2$ and $K > 0$ are tunable parameter, according to which different users' utilities are differentiated. It is also assumed that the utilities are normalised to their upper limit, i.e., the asymptotic value of $u(g)$ for large g (indicated in Eq. (3) as l) is taken to be equal to 1. This is only done for the sake of simplicity, in other more complicated scenarios also different maximum utilities can be considered.

We consider a rate allocation strategy based on the derivative of the utility. The role of $u'(g)$ is to describe the subjective perception of changes in the rate assignment. If $u_i'(g)$ is close to 0 for $g \geq g_0$, there is no point in giving more resource than g_0 to user i. The improvements due to increasing the resources beyond g_0 can be considered as negligible.

The evaluation of the point g_0 after which the incremental utility can be considered close to zero is still a degree of freedom for the provider, and there is a trade-off in its choice. For this reason we model the rate assignment performed by the greedy provider in the following way: a threshold value $\vartheta > 0$ is determined a priori by the provider, and the rate assignment proposed to each user i, g_i, starts from:

$$g_{i0} \triangleq \max(\{0\} \cup \{g \in]0, g_{max}] \, : \, u_i'(g) \geq \vartheta\}) \,. \tag{13}$$

Note that the threshold ϑ numerically translates the general bandwidth management strategy into a single parameter.

The sigmoid-shape of the utilities implies that the greater the value of ϑ, the lower the initial rate g_{i0} proposed to user i. That is, there is a trade-off for the provider in choosing ϑ. With $\vartheta \rightarrow 0$ the provider tries to supply users with very high utility. However, due to limitation in the total resource, such an assignment may prevent other users from entering the system, as there is no bandwidth left. On the other hand, too low rates, obtained with high threshold, save capacity for other users but decrease the acceptance probability.

The rate assignment policy depends on the kind of constraint for the radio resource, as previously discussed. In more detail, in this paper we distinguish between systems characterized by *hard* or *soft* capacity.

In the former case, users can be accepted as long as there are channels (time slots, or frequencies) available. This situation includes for example Time or Frequency Division Multiple Access (TDMA or FDMA). We can study such a system by imposing a constraint on the sum of the values g_i that can be allocated. Thus, the optimisation problem becomes for this case:

$$\begin{aligned} \max \quad & R \\ \text{s.t.} \quad & \sum_{i=1}^{N} g_i \leq W \, . \end{aligned}$$

For the rate allocation problem, W can be considered as the available bandwidth. However, in CDMA systems the probability that a new call finds the resource busy is negligible [13]. On the other hand, such systems are interference-limited, and the capacity is considered to be soft. That is, the hard theoretical limit to the number of users is worthless considered that there is another constraint, i.e., new calls should be blocked when their admission would cause an excessive degradation for already connected users.

In this work, we model the capacity of a CDMA-like system by considering the feasibility of the rate assignment in an interference-limited system. We translate the rate to signal-to-interference ratio (SIR) by means of the well-known Shannon's capacity formula:

$$\gamma_{t,i} = 2^{g_i/W} - 1 \, , \tag{14}$$

where $\gamma_{t,i}$ is the target SIR for user i. The rate values g_i are determined for one user at a time, by assuming that the allocation for user i happens after every user j, $1 \leq j < i$ has been considered. For each user i, the rate is initialised to the value g_{i0} determined by Eq. (13). If the set of the target SIRs for all users is feasible, this rate assignment is kept. Else, the new user's target SIR is decreased in steps of 1dB, until the system is feasible. Note that the rate assignments for already allocated users are not changed. Finally, the rate g_i corresponding to the SIR according to Eq. (14) is assigned to user i. Note that both utility $u(g_i)$ and price $p(g_i)$ are functions of g_i; thus, the service acceptance probability, expressed by $A(u, p)$, is affected by the changes in g_i.

For what concerns pricing, one should observe that pricing strategies include a lot of different proposals [14] [15] and it is not clear whether all of them can be considered realistic. Anyway, the basic property of a realistic pricing policy is a conceptual simplicity, that allows understanding and appreciation by the users.

In this work we discuss two different policies: a *flat price* strategy and a simple usage-based pricing where the price $p(g)$ is linearly related to g, i.e., $p(g) = kg$, with a given constant k. In particular, in the case of flat price, Eq. (11) can be rewritten by replacing p_i with a constant p. The effect of pricing is not neglected, as the value of p, defined a priori, can be subject to change. For linear pricing instead, p_i can be seen as $p(g_i)$, so that different prices are experienced by differently served users. The simplicity of these two policies implies their probable presence in next generation networks, even though a more complicated pricing scheme may turn out to be better for both the users and the provider. However, the model can be applied to every fixed pricing relationship known by the users a priori.

Parameter (symbol)	value
number of cells	19
bandwidth (W)	20 rate units
max assignable rate (g_{max})	8 rate units
cell radius (d)	500 m
gain at 1 m (A)	-28dB
Hata path loss exponent (α)	3.5
shadowing parameter (σ)	8dB
log-normal correlation downlink	0.5
log-normal correlation distance	25m
mean SNR at cell border	20dB
utility parameter ζ	$2 \div 20$
utility parameter K	$0.2 \div 4.2$
acceptance prob. parameter C	0.05
acceptance prob. parameter μ	2
acceptance prob. parameter ϵ	4

Table 1: List of Parameters of Simulation Scenario

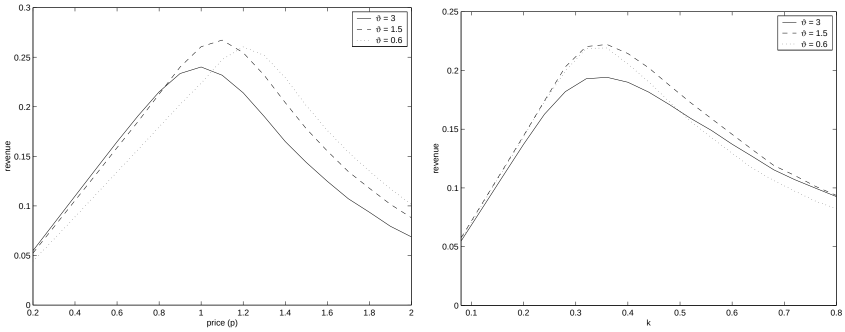
4 Results

Let us consider rate assignment in a CDMA-like system, and compare the performance of the two studied pricing policies. Table 1 shows the parameters of the simulation scenario. In particular, note that the users are uniformly distributed in a cellular area with hexagonal cells, that are "wrapped around" so that no border effect is introduced.

The first set of results presented investigate how the price affects the revenue. Figures 1(a) and 2(a) show the behaviour of the flat price strategy, whereas in Figures 1(b) and 2(b) the revenue for the usage-based pricing is plotted. In both cases, 120 and 180 users have been considered, respectively. It is emphasised that there is a pricing choice which maximises the revenue, as discussed in Section 2. Thus, the price variations adjust the revenue by means of the users' reaction depicted in our model by a change in the acceptance probability.

There is also a dependence on the provider choices in assigning the bandwidth to the users. In fact, it should be noted that, besides the price, also the threshold value affects the revenue: both the maximising price and the maximum achievable revenue change if the operator adopts a different threshold ϑ. The value of the threshold represents a measure of the QoS given to the users: in general $u(g_i)$ increases for decreasing ϑ, even though different users experience different qualities. Hence, the price and the rate allocation strategy should be carefully planned, possibly with a joint analysis.

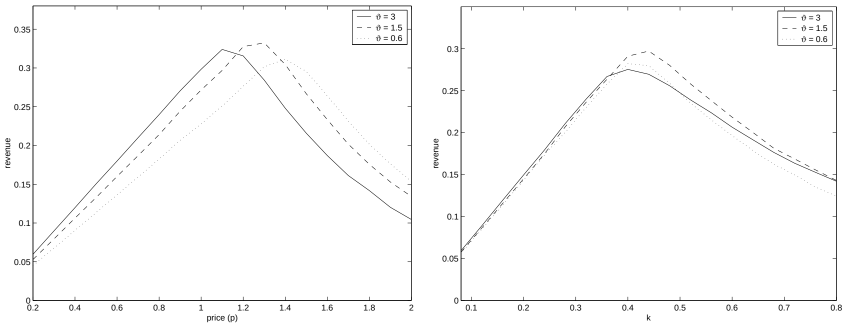
Figure 1(b) seems to suggest that, when the price is low, the usage-based pricing is less sensitive to the rate allocation parameter. In fact, a low p encourages the users to enter the system, so that the whole capacity is allocated. Thus, the revenue increases proportionally to k. However, note that the maxima of the curves, that are the interesting points for the provider, are placed differently for different ϑ. This means that the effect of the low price is to attract users into the system, with no or small consideration about the intrinsic QoS. With higher price, also the grade of service becomes important, and the highest value of the revenue is determined by both acceptable price and suitable rate assignment.



(a) Flat price, price on x-axis

(b) Price $p(g) = kg$, k on x-axis

Figure 1: Provider revenue for 120 users

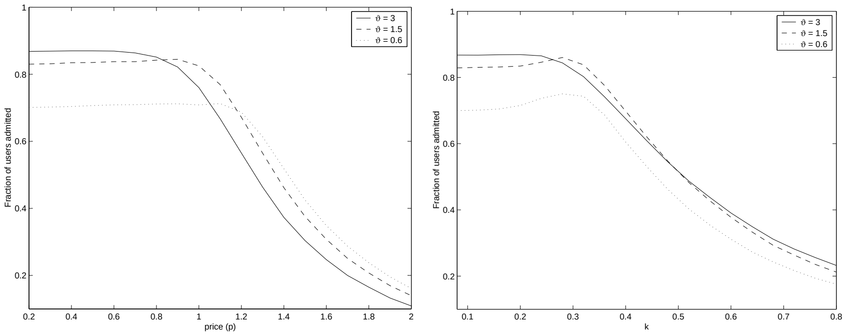


(a) Flat price, price on x-axis

(b) Price $p(g) = kg$, k on x-axis

Figure 2: Provider revenue for 180 users

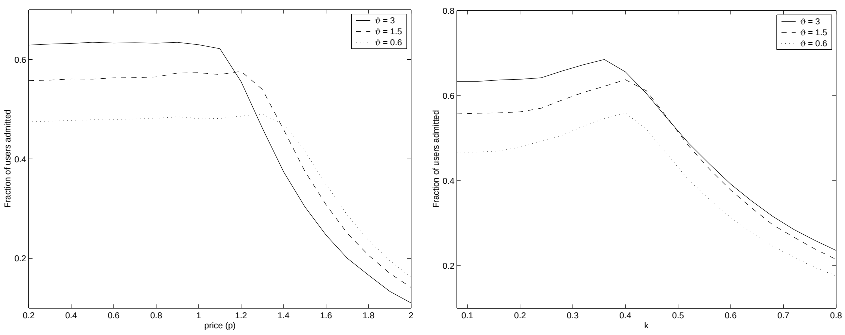
Figures 3–4 show, for flat and usage-based price, the fraction of users admitted into the system. In general, the higher the price, the lower the number of the users that accept the service. The trade-off in the choice of the utility that the provider assigns to each user (captured in the RRM with the threshold value ϑ) implies, however, different behaviours for different thresholds, even for a flat price strategy. For a low price the number of admitted users is constant and corresponds to a saturation of the bandwidth, so that some users can not be admitted. In this case, the lower the threshold, the fewer the users. A low ϑ generally means a high assigned rate. Therefore, few users are admitted in this case, whereas higher values of ϑ allow the admission of more users, though with lower quality. In Figures 3(a) and 4(a) this phenomenon is reversed at high price, i.e., there are more users for low values of ϑ. This happens because the decrease in the number of users is more consistent for threshold values that assign a poorer quality to the users. This does not occur in the usage-based price strategy since



(a) Flat price, price on x-axis

(b) Price $p(g) = kg$, k on x-axis

Figure 3: Admission rate, 120 users



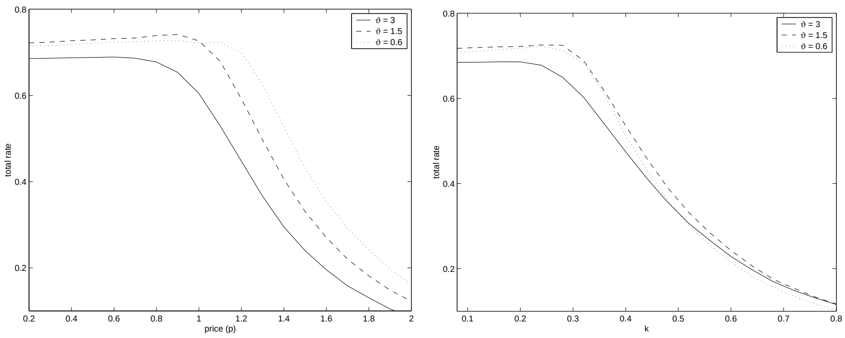
(a) Flat price, price on x-axis

(b) Price $p(g) = kg$, k on x-axis

Figure 4: Admission rate, 180 users

the price for low quality users is still lower. Finally, note that the maximum revenue is obtained approximately on the edge of saturation of the capacity, i.e., where the number of users starts to decrease. In this point, the effect of the decrease in admitted users overcomes the revenue increase due to higher price.

A similar behaviour can be observed in Figure 5, where the total assigned rate is represented for 120 users (the curves for 180 users are almost the same). However, whereas the fraction of admitted users has a monotonic behaviour as a function of ϑ for low price, the assigned rates are sorted differently. In particular, when the load is low, there is a more suitable value of ϑ (in the simulations, 1.5) that allocates a higher rate. For higher load the behaviour of different thresholds is approximately the same, even though $\vartheta = 3$ is the best choice. This means that the allocation of a total data rate close to the available bandwidth depends on the trade-off between the demand and the QoS assigned to the users (mapped by the parameter ϑ). Thus, the general choice of the



(a) Flat price, price on x-axis

(b) Price $p(g) = kg$, k on x-axis

Figure 5: Assigned rate, 120 users

allocated QoS is not trivial and can heavily affect the bandwidth dimensioning.

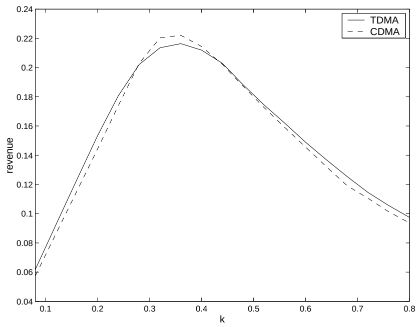
Finally, a comparison can be done between the TDMA-like and CDMA-like systems, i.e., between system with hard or soft capacity respectively. In Figure 6 we represent the application of usage-based policy to a CDMA network besides a network characterised by hard capacity (TDMA-like) with corresponding parameters.

First of all, it can be observed (Fig. 6(a)) that the peak performance of the CDMA-like network in terms of achievable revenue is higher. However, in general the performance is similar. A more interesting phenomenon can be observed in Figure 6(b), where it is shown that the “knee” present also in Figure 3(b) is not present in the TDMA-like network. This implies that a greedy strategy is not perfectly suitable for a soft capacity network. In fact, users that can be considered inefficient for the stability of the system should be refused. An interesting conclusion that can be drawn from these curves is that a higher pricing can even be useful, since it allows a better selection of the admitted users, increasing also the admission rate (that seems counter-intuitive).

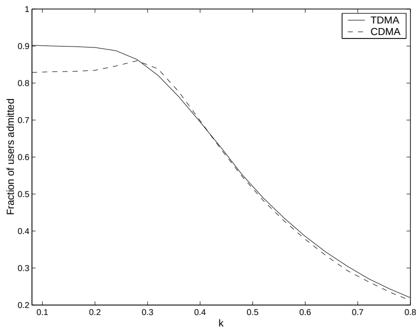
5 Conclusions

It is not trivial to determine the best usage of the network for the provider, that is the maximisation of the profit. The users’ response to both radio resource management and pricing has to be taken into account for its influence on the revenue. Thus, we introduced the *Acceptance-probability* model, which considers the joint effect of user utility and price. In this way it is possible to include economic considerations in the study of communications systems.

In this work the model was applied to compare different pricing strategies and systems characterised by different kinds of capacity (TDMA- or CDMA-like). The behaviour of the RRM is different when economic parameters like pricing strategies and user demand are taken into account. Thus, to efficiently control the performance of the system, the selection and tuning of RRM and pricing policies should be addressed jointly. From the point-of-view of a provider, this implies that the RRM can not be solved as a separate problem. Rather, the design of an appropriate resource allocation



(a) Provider revenue



(b) Admission rate

Figure 6: TDMA–CDMA comparison, price $p(g) = kg$, k on x-axis, $\vartheta = 1.5$

strategy needs several economic values as input parameters, like price and utility elasticity of the users, and also the shape of the utility functions. Even though econometric insights to evaluate these quantities are not so commonly and easily found, they could be very useful. On the other hand, note that the proposed framework is completely general, so that it can be applied to different specifications of utility and pricing relationships.

A general trade-off is identified between quality and price: users will not accept a high quality if they think it is too expensive. In fact, over-assignment can be considered wasteful: it hardly improves the revenue, but markedly deteriorates the admission rate. The appropriate setup of the pricing strategy is key to have a satisfactory revenue for the provider. Too high prices drive customers away (in the long run, likely to competitors), with low or no revenue as a result. Too low prices can easily be afforded by the users, but also yield very little revenue. Price variations also affect the expected number of users in the system; hence, they have to be considered in system dimensioning.

To sum up, the proposed model allows useful insights to be gained about the RRM strategy. The economic aspects of RRM should not be neglected, for they not only affect performance, but also require several strategic choices to be made. It is imperative for the provider to take into account these aspects; thus, our model can be useful to gain understanding of them and improve the RRM in real systems.

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