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Virtualization of spectrum for mobile operators: the pricing issue

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Abstract: Though wireless spectrum is an untangible resource, it is typically assigned through licenses on a long-term basis and may be likened to a property of the licensee. The possibility to lease it temporarily through a secondary market makes it a virtualizable resource, exploitable by virtual operators. A crucial issue for the business propositions of virtual operators is spectrum pricing. Spectrum leasing may take place in spot markets, where the sale is conducted in a single step, or through a reservation process, with a two-stage mechanism aiming at protecting the prospective buyer against the price fluctuations of the spot market. In spot markets the price is set either through auctions or by direct imposition by the license holder, with the aim of maximizing its revenues. In reservation procedures, the price can instead be set as a fair price through the no-arbitrage principle.

Keywords: Mobile Virtual Network Operators, Spectrum Trading, Pricing

1 Introduction

Virtualization in mobile networks may represent a way to provide new network and application services [KWKJ09]. All the resources in a mobile network can now be virtualizable: the physical nodes (mobile switching centers and routers) and their components (down to CPU, storage facilities, etc), the access devices, and the links and paths that connect them. Such is the vision that stays behind current research projects as 4WARD [SGP+08].

A number of stakeholders may take advantage of virtualization by exploiting virtualized resources. For example, a fixed network operator may use an access infrastructure it doesn't own to add mobile services to its portfolio; a mobile operator that owns an infrastructure may need additional resources to meet its demand peaks; a company currently outside the telecom business may exploit its brand and resell services offered through a mobile operator's network. Wherever a company sells services without owning the infrastructure used to provide them (i.e., it is hiring an operator's infrastructure), we may say that it is operating in a virtualized context. Mobile Virtual Network Operators (MVNO) possess very limited network facilities or none at all (see, e.g., [BD09] and [Di 08] for a classification of MVNOs and an illustration of their range of activities), and are therefore compelled to rely on the virtualization paradigm to operate. In addition to being considered as a profitable activity [OKV+06], the presence of MVNOs has been deemed as relevant for the development of the 3G mobile business [Har02].

Wireless spectrum, though being an intangible asset, is one of the resources that may be virtualized. Its use is necessary in the access portion of the network. At first, spectrum in wireless networks was assigned on a long term basis, and with exclusive rights, to a limited number of

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mobile operators (the licensees), typically through auctions. Such assignment compelled the licensee to build its own network infrastructure and start the service. Transfers of license were forbidden. This prohibition has later been removed for a number of reasons. It has also been shown that allowing the licensee to resale the spectrum it had been assigned adds value to the license itself on the primary market [Val01] [MN10d]. Hence, a secondary market for spectrum is now a reality in many countries (see the brief survey in [Cro09]). Though the licensee retains the usage rights on the spectrum portions conferred to it, it may then transfer them temporarily to other operators. Spectrum is now a tradable resource and may then be virtualized. A mobile operator can provide services without having been assigned spectrum in the first place, but renting the spectrum assigned to other operators, on the secondary market.

A crucial issue for the profitability of spectrum virtualization is the price of spectrum. Setting it too high reduces the profit oof the virtual operator. On the other hand, too low a price may make spectrum leasing not appealing for the licensed operator. The correct determination of the price may make the difference as to the viability of the business model of virtual operators. However, they address specific contexts in the absence of a general framework.

The aim of this paper is to explore the pricing issue for wireless spectrum, and provide a first step to build a taxonomy of pricing methods. Such taxonomy is needed both to put the individual contributions in place and recognize their limitations, and to see the gaps in the current analysis of the pricing issue. We consider the case where a licensed operator leases its spectrum to a virtual operator. Here the term is used with reference to spectrum alone: a virtual operator doesn't own rights of usage on the spectrum it uses and is compelled to purchase them from a licensed operator. We identify the main factors making up the framework we have to employ to define a pricing method, and perform a brief review of the pricing methods appeared in the literature. We observe that the passage of spectrum from a licensed operator to a virtual one may take place basically in two different ways, i.e., either on the spot market, or through a reservation process (spectrum is first booked, and later, if actually needed, bought): what is traded is the spectrum itself in the former case, and the reservation right in the latter case. We show that two basic pricing approaches emerge: the price can be set either as the result of a utility maximization strategy or as the outcome of a protection strategy through the no-arbitrage principle.

The paper is organized as follows. In Section 2 we illustrate the different facets of spectrum trading for MVNOs. In order to illustrate the pricing proposals appeared in the literature so far, we rely on the entity being traded. We describe pricing approaches for spectrum itself in Section 3; in Section 4 we consider instead pricing of reservations, where the temporary purchase of spectrum is carried out in two stages.

2 Spectrum virtualization in mobile networks

Setting the correct price depends on a number of assumptions. It is helpful to define the range of situations that may apply, both to frame the contribution of each paper and to delineate a taxonomy of possible areas of investigation. In this section we try to identify the most relevant facets of spectrum pricing in the context of virtualization.

The factors we deem as most relevant to set the price of spectrum in a secondary market are the following:

- Players;
- Market power;
- Object of transaction;
- Rights transferred through the transaction;
- Viewpoint.

We now examine each of them separately.

The players in this market are just service providers. Namely, the license assignees are the primary owners of usage rights on spectrum, and act as sellers. Instead, the buyers are virtual operators. Please note that here and in the following we use the terms *buy* and *sell*, though the transaction is actually a lease, i.e., a temporary transfer of usage rights. End users enter the picture just as determining the end demand for spectrum for both buyers and sellers. The effects of demand are not symmetric for the two sides: a demand low for license assignees spurs them to sell the underused spectrum, while virtual operators are compelled to buy spectrum by their very nature. In fact a virtual operator doesn't own any spectrum in the first place, and is compelled to buy it even if its demand is very low. The set of players is quite different from what is considered in most papers on pricing in wireless networks, where the buyers are end users. Here the size of the market is then limited to a few operators (say, of the order of ten at most) rather than the large population associated to mass services.

The market power determines the capability of the seller to set the price. We can range from a monopoly situation, where we consider a single buyer and all the virtual operators act as price takers, to a competitive environment, where multiple license assignees are willing to sell spectrum. In most situations we have a limited number of license assignees (e.g., three or four), so that some degree of competition exists.

The transaction carried out by the licensed operators and the virtual ones may concern the usage of a communication channel over different portions of the access network. For example, the licensed operator may lease spectrum over a whole network, or just a single cell. In addition to this spatial feature, we have to define what is the spectrum resource the usage of right referes to. In the case of FDMA (Frequency Division Multiple Access) the object for sale may be even a single frequency within the set assigned to the base station. This is also the case in DMT (Discrete Multi Tone) or OFDM (Orthogonal Frequency Division Multiplexing), where the object for sale is a set of sub-carriers. Instead, in the case of CDMA (Code Division Multiple Access) the bandwidth available for communication is actually shared by a number of users, each of which uses it all. But, since the code domain is splitted into a number of spreading codes, each making up a communication channel, we can consider the spectrum to be used proportionally to the number of spreading codes assigned. The pricing approach to wireless spectrum can therefore be used in the case of CDMA access as well.

Whatever the object for sale, the transaction may transfer the usage rights for that object or simply the reservation rights for it. In the former case the virtual operator pays a price to use the object (e.g., a block of frequencies on a cell) for the time determined by the contract associated to the transaction. As an alternative to the immediate purchase the virtual operator can instead pay a (lower) price to book the object, to be bought at a later time. It is to be noted that in

reservation contracts the virtual operator acquires the right, but not the obligation, to actually purchase the object later. When the time comes, the virtual operator may decide to let its right down and not to purchase the spectrum, e.g., because the demand due to its customers is not up to the expectations. The type of rights we envisage here is just a subset of a much larger picture, where we consider the whole variety of players that may be involved in spectrum management: in the more general framework spectrum can be shared in a variety of ways, and in some cases no rights are assigned. A more complete taxonomy of spectrum management models is described in [Bud07].

Finally, we can adopt the viewpoint of the license assignee or that of the virtual operator. The license assignee, acting as a seller, tries to maximize its profit, and has a large degree of autonomy if it's acting as a monopolist; the virtual operators are price takers, and influence the price just by modifying their demand curve. For the virtual operator, the price of spectrum is a cost that it tries to minimize, hopefully by exploiting the competition among license assignees. A different approach can be considered where a fair price is sought after: the price is set according to the value that spectrum has for either the license assignee (i.e., its opportunity cost derived from the alternative use of that spectrum) or the virtual operator (i.e., the value determined by the revenues it expects to get by operating that spectrum).

In the following we adopt the type of rights transferred as a primary factor to categorize the studies conducted on pricing. Hence, we distinguish primarily between purchase contracts, which we deal with in Section 3, and reservation contracts, which we deal with in Section 4.

3 Pricing on a spot market

The first class of pricing mechanism we consider refers to a spot market, i.e., to the case where the spectrum units are sold in a single step. In this section we describe the most relevant approaches proposed in the literature. We will refer to the owner of usage rights as the seller or the primary operator, while the operator acquiring the spectrum on the secondary market will be referred to as the buyer or the secondary operator.

A major subdivision concerns the mechanism employed to set the price. We have basically two different approaches, where the price is either set by the seller or resulting from an auction (hence, indirectly set by the buyers themselves).
In the first group we find the works by Mutlu et alii [MAS09], by Daoud et alii [DAS10b], and by Duan et alii [DHS10]. Instead, the auction approach has been considered by Sengupta and Chatterjee [SC09], Jia et alii [JZZL09], and by Gandhi et alii [GBC+08]. We now examine separately the two groups of contributions.

In the three papers where the price is set by the primary owner of usage rights, the secondary operators act as price takers. In [MAS09] and [DAS10b] the price is set as that maximizing the profits of the primary operator. Instead, in [DHS10] the viewpoint of the secondary operator is adopted: a couple of secondary operators is considered, which receive a different unit price for spectrum from a primary operator and then seek an optimal decision leveraging on the quantity of spectrum that they buy and on the price they charge in turn to their end users (a three-stage dynamic game is considered). In both [MAS09] and [DAS10b] the demand for spectrum by the secondary operators is considered to be elastic with respect to the price (hence a demand curve

is known to the primary operator, rather than a specific spectrum quantity request). The primary operator continues carrying on its own traffic in addition to that due to the secondary operators' end users, but the negative externality associated to the interference and the increased blocking probability for the primary operator's end users reduces the primary operator's revenues. A number of alternatives are explored for the price. Both in [MAS09] and [DAS10b] single price policies are considered. In [MAS09], a single price per call is charged either till the spectrum is fully used (named *static pricing*) or till a specified level of spectrum occupancy is reached: the latter case (named *threshold pricing*) has the aim of protecting the quality of service for the primary operator's end users. The authors show that threshold pricing provides larger revenues than static pricing (in threshold pricing an optimal decision has to be taken both for the unit price and for the threshold level). Instead, in [DAS10b], the leasing of entire cells is considered, and the price refers either to the single cell, or to the traffic unit. In any case, the decision to lease, though conducted with the optimal pricing decision, may lower the revenues for the primary operator.

Where the use of auctions is envisaged, the aim is anyway to maximize the revenues of the primary operator. An auction is supposed to be held periodically, with sealed bids. In [SC09] and [JZZL09] the bidders declare a specific value for the (*Price*, *Quantity*) couple; in [GBC+08], the secondary operators are instead expected to declare the demand curve. The price determination follows the second price paradigm in [SC09] and [JZZL09]. Namely, in [SC09] the allocation of spectrum is approached as a knapsack problem, where the allocation leading to the maximum revenues is chosen, within the constraint of the overall available capacity. In [JZZL09] the Vickrey-Clarke-Groves (VCG) is first considered, but an alternative, computationally lighter pricing algorithm is then proposed, which shares with VCG the truthfulness property, i.e., that the bidder is led to declare its actual valuation of the spectrum rather than a lower value. Instead, in [GBC+08] the clearing price is set by the seller, either as a single price for all the bidders or as a differentiated price, and the bidders receive a fraction of the overall spectrum in relation to the distance of their bid to the clearing price.

4 Pricing reservation contracts

Reservation contracts represent the alternative to spot sales. The sale is accomplished in two stages: the reservation itself and the actual later sale. The reservation represents a right and therefore is not necessarily followed by the sale. The acquisition of reservation rights has a price tag as well. In this section we describe the methods proposed in the literature to set that price.

In a reservation contract the license holder sells the virtual operator the right to buy a block of frequencies at a later time. That reservation is tantamount to what is termed a *call option* in the financial market. The virtual operator pays a price for that reservation. If it later decides (when the reservation expires) to buy that portion of spectrum it pays again a price (the *exercise price*), determined at the time of the reservation. It is again to be remarked that the reservation gives the virtual operator the right but not the obligation to fulfill the purchase: if at the expiration time the virtual operator decides not to proceed with the purchase, it owes nothing else and can walk away from the reservation contract. A variation of this basic reservation contract may be envisaged where the license holder may renege to sell the spectrum that had been booked by the

virtual operator. There may be a number of reasons for that behaviour. For example, the license holder may face a demand much larger than the low that had spurred it to lease that spectrum in the first place, and may find it more remunerative to use the spectrum to satisfy the demand of its own customers rather than lease it. Or the spot price of spectrum may be much larger than the exercise price, so that the license holder finds it more profitable to sell that spectrum on the spot market. Or it may happen that the virtual operator has accepted bookings for much more spectrum than what is available for leasing (a practice commonly known as *overbooking* and taking place in other contexts as well, such as flight bookings); in that case it cannot satisfy all the virtual operators that had booked. In any of these cases the reservation is *vulnerable*, i.e., the guarantee it offers is not absolute. In order to distinguish between that case and the case where the virtual operator is fully sure to be able to buy the spectrum if it wants to, we use the terms reservation with *soft* and *hard* guarantees respectively. We expect the price of reservation with hard guarantees to be larger than the other case. But in the case of soft guarantees the unsatisfied virtual operator is compensated by a penalty paid to it by the license holder. The flows of money between the virtual operator and the license holder (indicated simply as MNO, Mobile Network Operator) are illustrated in Figure 1 and Figure 2 respectively. In those pictures the dashed lines represent event-driven flows, i.e., events that may not take place. Namely, in Figure 1 the payment for spectrum takes place only if the MVNO decides to exercise the option, while in Figure 2 either of the two dashed flows takes place iff the MVNO decides to exercise the option: the payment for spectrum if the spectrum is available, and the payment of the penalty if it is not.

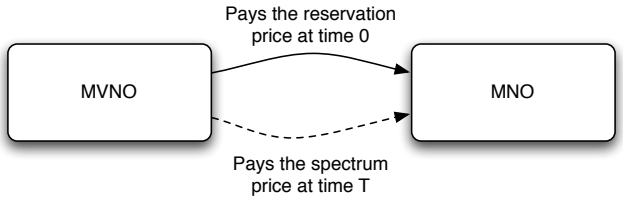

Figure 1: Money exchanges between the MVNO and the MNO in reservations with hard guarantees

In [MN10c] the overbooking strategy and the no-overbooking have been compared considering a model for the correlation among the demands expressed by several virtual operators. The extra revenues due to overbooking appear to be linearly dependent on the penalty and on the unit spectrum price (with a negative and a positive slope respectively). Instead, a threshold may be located for the overbooking ratio (i.e., the ratio between the amount of spectrum that the virtual operators have booked and the amount that the license holder can sell), such that for ratios lower than the threshold the overbooking gain increases significantly, decaying fast as that threshold is exceeded. For the cases examined the threshold corresponds to not so small overbooking ratios (roughly 1.5 to 3), so that significant margins exist for the application of the overbooking strategy. The correlation among the virtual operators' decisions negatively affects the gain due to the overbooking strategy especially when it gets larger.

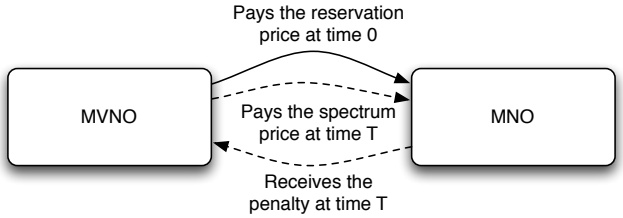

Figure 2: Money exchanges between the MVNO and the MNO in reservations with soft guarantees

A relevant choice by the license holder concerns setting the capacity of the cell that may be safely leased. The license holder is spurred to lease capacity when it is underusing it, so that the license holder has to strike a balance between the revenues it would get by operating itself that capacity and the ones it gets by leasing it to the virtual operator. The balance provides room for an optimal decision as that maximizing the license holder's revenues. In [DAS10a] the optimal reservation policy for license holders is defined taking into account the interference caused by secondary users. Though the analysis is conducted without specific reference to the case of virtual operators, its methodology may be employed to derive guiding principles in our case as well.

The issue of pricing of reservations is dealt with in [MN10b]. The solution is based on the *real options* approach, where the price is set under the no-arbitrage principle. i.e., so that, if the spectrum spot price dynamics is as assumed in the model, the virtual operator would find it equivalent either to buy the spectrum through the reservation process or to buy it on the spot market. The price set through the no-arbitrage principle can then be considered as a fair price, which embodies a protection mechanism (against excessive fluctuations of the spot price) rather than optimizing profits of one of the two parties. The resulting reservation price is a function of the exercise price (i.e., the price to be paid for the spectrum if the virtual operator decides to proceed with the purchase), the reservation expiration time, the penalty to be paid in the case of overbooking, and the market conditions (the volatility and the risk-free rate). The resulting reservation price is a fast decaying function of the overbooking probability (the probability that the virtual operator is left without spectrum because of overbooking), with a decay rate that gets larger as the expiration time gets shorter, as can be seen in Figure 3, where the reservation price is given as a percentage of the agreed exercise price. For sake of comparison, the reservation price for hard guarantees is 2.51 (expiration time of 1 month) and 1.154 (expiration time of 1 week). Instead, increasing the ratio between the penalty and the reservation price leads to increased reservation prices, though the effect may be minimal over very short timescales.

5 An application scenario for a Mobile Virtual Network Operator

In Section 4 we have seen that a reservation mechanism may be employed by a MVNO to get the spectrum it needs and protect itself at the same time from spot price fluctuations. For such

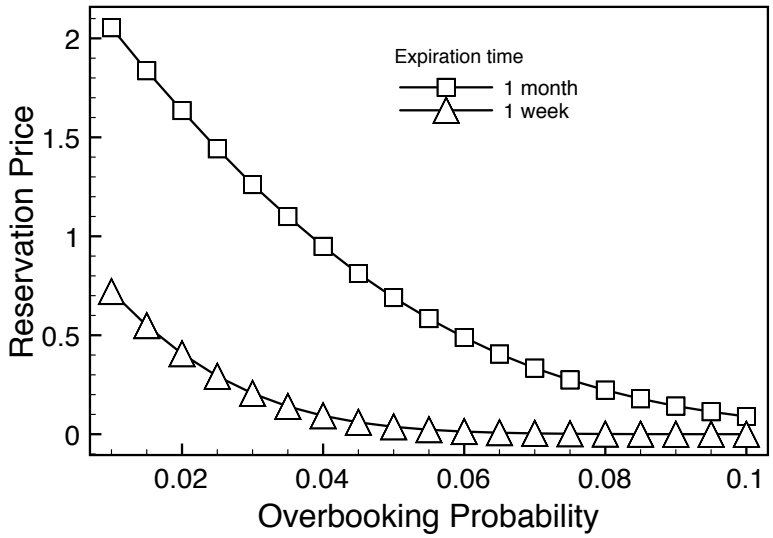

Figure 3: Impact of the overbooking probability on the reservation price

mechanism a fair price can be set by resorting to the no-arbitrage principle. and using the real options tool. However, reservation contracts come with two flavours: the MVNO can stipulate a reservation contract with either hard or soft guarantees and has then to opt for the better between the two. In this section we report the results of a comparison of the two kinds of contracts.

By adopting the price setting mechanism defined in [MN10b], a comparison between the two reservation contracts, examined from the viewpoint of a MVNO, has been carried out in [MN10a]. In that paper the profits obtained by a MVNO, under either hard or soft guarantees, are compared to identify the more profitable type of contract and the most relevant driving factors. The cash flow for the MVNO considered in the hard guarantee case (no overbooking) are:

1. Expense to buy the options (towards the MNO);
2. Expense to exercise the options (towards the MNO);
3. Traffic-generated revenues (from the end customers).

On the other hand, in the soft guarantee case (with overbooking) the cash inflow associated to the penalty for the undelivered channels (coming from the MNO) has to be added.

The comparison takes into account that, when overbooking is employed, the MVNO is assigned less channels than what it needs to accomodate the traffic coming from its customers. The reduction of channels entails an increased blocking probability and a reduction of traffic-related revenues, which is then taken into account in the overall profit evaluation.

In the sample scenario considered in [MN10a] tha major decision factors to opt for either reservation contract are the expiration time of the reservation (i.e., the time advance adopted to book the channel) and the overbooking probability, i.e., the probability that the MVNO is denied the channel it had booked. The impact of the penalty value is much less relevant, but we have to

remind that the reservation price already incorporates the effect of the penalty: reservations with soft guarantees and a penalty are sold at a quite lower price than reservation with hard guarantees.

As to the domain of preference for either type of contract, we can see two sample results in Figure 4 and Figure 5, again in the scenario considered in [MN10a]. In both papers the relative profit for the MVNO of a soft reservation contract over that associated to a hard reservation contract is shown. Namely, in Figure 4 we see that contracts with soft guarantees are preferable for longer expiration time. Instead, in Figure 5 we consider the relative profit as a function of the overbooking probability. Here the trend is not monotonic. Though, as expected, the soft reservation contract is preferable for smaller values of the overbooking probability, there is an optimal value of the overbooking probability that maximizes the MVNO's profits.

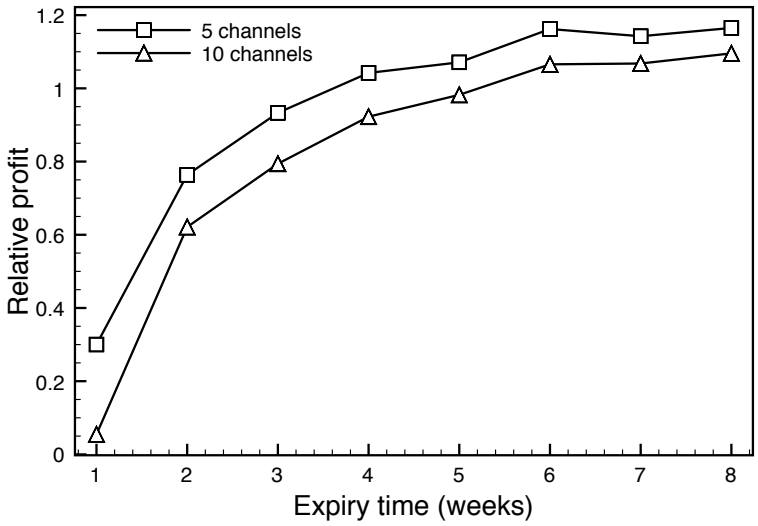

Figure 4: Impact of the expiration time on the relative profit

6 Conclusions

The two basic categories of contracts for spectrum have been reviewed: purchase contracts accomplished on the spot market, and reservation contracts, where the purchase is fulfilled in two stages. The pricing methods proposed for spot markets have considered the price as set either directly by the license holder, as the result of an optimization procedure, or through auctions, mainly by a second-price mechanism. Though in auction the prices are determined by the bids submitted by the virtual operators, in both cases the aim is the maximization of revenues maximization for the license holder. Instead, the approach mainly taken in pricing algorithms proposed for reservation contracts is instead to set a price, which both the seller and the buyer recognise as fair, where the aim is to protect the prospective buyers (i.e., the virtual operators) against price fluctuations. A degree of protection can be included for the license holder in reservation

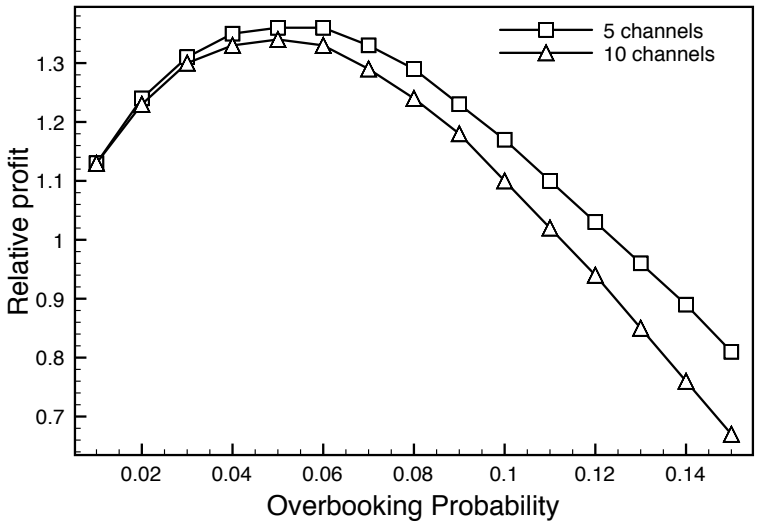

Figure 5: Impact of the overbooking probability on the relative profit

contracts as well, through the adoption of overbooking policies, which in turn lead to reduced reservation prices. A simple business case for virtual operators, showing where overbooking may be convenient for the buyer, has been considered.

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