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Network Slicing: Is It Worth Regulating in a Network Neutrality Context?

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Abstract

Network slicing is a key component of 5G-and-beyond networks but induces many questions related to an associated business model and its need to be regulated due to its difficult co-existence with the network neutrality debate. We propose in this paper a slicing model in the case of heterogeneous users/applications where a service provider may purchase a slice in a wireless network and offer a “premium” service where the improved quality stems from higher prices leading to less demand and less congestion than the basic service offered by the network owner, a scheme known as Paris Metro Pricing. We obtain thanks to game theory the economically-optimal slice size and prices charged by all actors. We also compare with the case of a unique “pipe” (no premium service) corresponding to a fully-neutral scenario and with the case of vertical integration to evaluate the impact of slicing on all actors and identify the “best” economic scenario and the eventual need for regulation.

1 Introduction

Wireless communications are currently a widespread global phenomenon, with demand for wireless connectivity constantly increasing. 5G (and beyond) networks aim to address this

demand by providing a much higher available throughput compared to previous generation networks, enabling the delivery of a broad range of new and advanced services such as real-time interactivity or autonomous driving [16].

For many new services, there is a requirement for resource provisioning and guaranteed quality of service: *network slicing* is the key concept and important component of 5G and beyond networks towards this goal. Network slicing consists in creating multiple dedicated logical and virtualized networks over several domains, cutting the infrastructure into “slices” managed independently. Slices are tailored to the specific quality requirements of applications or services in order to align resources with needs [22]. Among use cases, slicing is expected to lead to higher bandwidth for video, better speeds for some applications, a possible wide-scale availability and guaranteed quality of service.

Slicing, as one of the main characteristics of 5G and beyond networks, also means the design of an associated business model and is an opportunity for return on investment for network operators (or Internet Service Providers, ISPs) in front of infrastructure costs; it indeeds provides a new economic possibility for network operators to get more value out of the transport of services and have more control on their network. The types of questions we aim at answering are: how should a slice be charged and how much should be allocated to maximize the network owner revenue? Is it viable for the slice tenant? What is the impact on users and in terms of social welfare?

On the other hand, network slicing raises concerns about the infringement of neutrality principles driving the Internet [11]. Basically, network neutrality means that Internet Protocol (IP) packets are treated equally within the network, regardless of the type of content, origin or destination, and type of platform, application or device they are related with. Slicing does not seem to fit that framework, due to the specific treatment of flows in the slice. This concern is starting to be heavily discussed in the literature [21, 6, 17]. The regulators, aware of the apparent contradiction between slicing (that is, reserving resources) and neutrality, have introduced the notion of so-called *specialized services*, also called sometimes managed services, to “bypass” neutrality. They are considered as “non-broadband Internet access services” or “services other than Internet access services” [18] to limit their perimeter to situations where

the optimization is necessary in order to meet requirements of the content, applications or services for a specific level of quality. It is not our purpose to discuss the validity of specialized services in a neutrality context (see the above references), but we can investigate its economic impact on all actors and society, hence the interest or not to regulate slicing.

Our contributions are therefore the following:

- We propose a model for network slicing where an ISP owning the network infrastructure can sell a part of it, a slice, to a service provider (SP) which can offer an upgraded service with respect to the regular one of the ISP. The model also involves end users sensitive to price and quality of service and heterogeneously separated into two classes depending on their requirements. Each user chooses among three options—the service offered by the slice, the “regular” one, or no service if price is considered too large for the given quality. From the user point of view, the model corresponds to the so-called Paris Metro Pricing scheme, which separates the network into independent subnetworks, each behaving identically, except they are charged differently so that the most expensive is expected to be less congested and thereby to offer a better quality [12, 15]. Given that decisions from the various actors are taken at different time scales, the model is analyzed as a Stackelberg game, i.e., with actors who make the large-time-scale decisions anticipating the subsequent reactions of the other players, thereby acting as “leaders” (the subsequent decision makers are then “followers”). Our model presents the advantages of being simple and of allowing to determine optimal strategies in terms of the slice size and of prices set by providers.
- The model allows to encompass two other scenarios, in particular in the network neutrality context where no slice is expected. We therefore study the same type of model but without the slice (that is, the SP) component, and recompute the optimal decisions and prices in this restricted case. We compare the revenues and social welfare to investigate whether slicing is a society worthwhile addition and/or if it should be regulated.
- We also investigate what happens equivalently when the ISP itself offers the upgraded service, which means a vertically-integrated scenario where the SP and ISP are the same

entity, modifying the impact of decisions. We will see whether the vertical integration harms social welfare or not and compare it too with the neutral scenario to determine which option should be pushed.

The numerical investigations carried out from our model suggest that the service differentiation allowed by slicing (even through a simple Paris Metro Pricing quality differentiation only due to prices differences among slices) yields added value to the overall system, as user welfare increases with respect to a neutral (no slices) situation. Somehow surprisingly, over the scenarios we have tested, the one where the ISP and SP are integrated (naturally preferred by the ISP) leads to the largest user welfare values, even above a situation where the ISP-level decisions are taken by a regulator.

The remainder of the paper is organized as follows. Section 2 reviews the related work and highlights the contribution. Section 3 presents the model, defining the set of actors (or players) made of end users, ISP and SP, their utilities, and describing the hierarchy of decision-making. Section 4 analyzes the game by backward induction. Section 5 compares the output of the game with the situation where the ISP and SP are integrated and with the case where slicing is not allowed, to investigate if and how it impacts the various actors. Section 6 additionally analyzes what happens when the slice prices are fully or partially regulated. Finally Section 7 concludes and proposes extensions of the present work.

2 Related work

The deployment of network slicing has significant implications on the economics of network infrastructure and services. By allowing network operators to offer customized slices with different service levels, network slicing creates new opportunities for revenue generation while allowing to meet a wide range of use cases. But the economics of slicing induces new challenges in terms of resource allocation, pricing, and competition between slices.

Surprisingly, the literature on charging for network slices remains quite limited. The paper [9] nicely covers and surveys all uses of economic models (mainly game theoretic ones) for user association (determining the base station to associate a mobile user), spectrum allocation,

power management and wireless caching, but slicing is not directly addressed.

In [3, 4] slicing is managed by intermediaries, named Network Slice Tenants (NSTs), and the infrastructure provider (the ISP) allocates resources to those NSTs according to their customers. A network made of several cells is considered and NSTs can have heterogeneous demands on each cell. A Stackelberg game is played with the ISP as the leader on the allocation, and the NSTs as followers on the repartition among their own customers. The price is considered there fixed by an authority.

But most papers are based on auctions. For example [2] also deals with NSTs, with a framework based on the Kelly mechanism [8] where slice tenants submit a bid to the ISP and are allocated an amount of resource defined as a fraction of the whole resource proportionally to the received bids; what they pay also depends on how much they bid. A general standard auction framework is first considered in [19] with NSTs buying resource to the ISP and reselling it to users, still through an auction; It is shown that the desirable properties of incentive compatibility (bidders being incentivized to behave truthfully) and efficiency (the resource being optimally allocated at equilibrium) cannot be simultaneously achieved. Then two hierarchical mechanisms with efficient Nash equilibria, inspired by the Vickrey-Clarke-Groves scheme [20], are proposed. Another, this time revenue-maximizing, auction is proposed in [7] where the resource is separated in chunks. Paper [23] on the other hand presents a more specific auction mechanism designed for Mobile Virtual Network Operators (MVNOs), but easily transcribes to the slicing context: each MVNO (or slice) has predefined customers, and hierarchical combinatorial auction mechanisms are designed to allocate communication subchannels, power, or antennas. The problem is solved through dynamic programming.

This paper is an extension of the conference paper [5] where the same type of model is analyzed, but considering two classes of users/applications with different sensitivities to quality of service. Actually dealing with more heterogeneous classes like this seems to us a relevant extension justifying the potential need for slicing and an upgraded service. Users are not forced to a specific (sliced or not) service, the decision is up to them and taken non-cooperatively. This multiclass context considerably complicates the user equilibrium—the determination of the repartition among the service options—and impacts the optimal decisions

with respect to [5]. It also changes the expression of social welfare. The model proposed in this paper is analyzed as a Stackelberg game, but not based on an auction. Its advantages include simplicity and the ability to determine optimal strategies in terms of the slice size and prices set by providers. The model also allows for the comparison of scenarios with and without slicing, as well as a scenario involving vertical integration of the SP and ISP.

3 Model

This section is devoted to the case of network slicing and describes a game-theoretic model with the goal of each actor, the order of decisions, and the corresponding analysis.

3.1 Actors and decisions

We consider three types of actors, namely one ISP (network provider), one SP (service provider) who would want to acquire a slice from the ISP to create the premium service, and users. We specify below the assumptions we make about each actor.

- The **ISP** has a fixed communication capacity, denoted by C . That capacity can either be used as a capacity- C “pipe” for all users, or it can be split through slicing, with a slice of capacity C_s sold to the SP as a separate logical network. Capacity can for example be expressed in Gbit/s, and may depend on several factors like radio conditions, modulation and coding schemes. Our model is general, the effects of the used communication technology are encapsulated into the communication capacity value. We do not specify the capacity unit, so that the model adapts to the communication technology considered. We denote by $p(\cdot)$ the capacity price function that is applied by the ISP to the SP, so that the latter would be charged $p(C_s)$ for a reserved slice. That price function may be a decision variable for the ISP, or be regulated.

Another decision variable for the ISP is the price charged to users for connecting to the Internet, that we denote by q_I .

- When the **SP** purchases a capacity C_s , its utility is its net revenue $R_{\text{SP}} = -p(C_s) + d_{\text{SP}}q$, with q the unit service price charged to users, and d_{SP} the user demand for the premium

service.

• **Users** are considered as a continuum of mass 1 (without loss of generality) but considered of two types, H with high sensitivity to congestion, of mass θ_H , and L to low sensitivity to congestion, of mass θ_L , such that $\theta_H + \theta_L = 1$. Each user of each type has to choose among the available options (basic service, premium service, no service); those choices are modeled with an attraction-based approach that allows us to express the proportion of users making each choice [10]. More precisely, each choice option is associated with a user utility that depends on some objective metrics like the data rate and the price, but also on some personal preferences that are modeled as random variables. Specifically, we model the utility of a user choosing the “premium” option (offered by the SP, for a price q to be paid in addition to the q_I paid to the ISP) as

$$u_{\text{SP},i} = \alpha_i \ln \left(\frac{C_s}{d_{\text{SP}}} \right) - \gamma \ln(1 + q + q_I) + \kappa_{\text{SP},i}, \quad (1)$$

where α_i represents the sensitivity to the throughput per service unit $\frac{C_s}{d_{\text{SP}}}$ for a type- i user ($i \in \{H, L\}$), with d_{SP} the total demand for that service; γ is the user sensitivity to prices and is assumed the same for both types of users, and $\kappa_{\text{SP},i}$ is a user-specific value (random variable) assumed to follow a standard Gumbel distribution independent of all other values. Using a logarithmic function in terms of parameters comes from psychophysics, where it has been shown that the perception of a physical stimulus is logarithmic in its magnitude [14]. Considering a Gumbel distribution for the random part is common in discrete choice theory (typically in the multinomial logit model), and mathematically convenient as it leads to closed-form expressions for the repartition of users among the discrete set of choices [1] (see below).

Considering two classes, with typically $\alpha_H > \alpha_L$, means that type- H users are more sensitive to quality than type- L ones; the random component brought by the Gumbel random variable introduces more heterogeneity though.

Another choice for a user of a type- i , which we will label as choice 0, is the “basic connectivity” service, charged by the ISP at a price q_I and leading to a utility of the same form as before:

$$u_{0,i} = \alpha_i \ln \left(\frac{C - C_s}{d_0} \right) - \gamma \ln(1 + q_I) + \kappa_{0,i}, \quad (2)$$

with d_0 the user mass for that choice (note that the capacity $C - C_s$ is what remains after C_s has been reserved by the SP), and κ_0 another independent Gumbel-distributed random variable.

The third possibility for a user is not to benefit from any service, an option denoted by N , that will be treated as the reference situation without loss of generality, hence yielding a null deterministic part of the utility to which we again add a user-specific (subjective) term, leading to

$$u_{N,i} = 0 + \kappa_{N,i}. \quad (3)$$

Each user, knowing their own realizations of $\kappa_{\text{SP},i}$, $\kappa_{0,i}$ and $\kappa_{N,i}$, selects the option yielding the largest utility. A consequence of those variables being Gumbel-distributed is that demand will spread proportionally with the exponentials of the non-random part of utilities: if each option $o \in \mathcal{O}$ has a utility of the form $\beta_o + \kappa_{o,i}$ for user i , then the proportion of users preferring option o is

$$\frac{e^{\beta_o}}{\sum_{j \in \mathcal{O}} e^{\beta_j}}. \quad (4)$$

(For this standard derivation please refer to [1].)

3.2 User equilibrium

With such a model, selfish choices from all users would lead to the following repartition over the three options, with $C_0 := C - C_s$ to simplify notations. Plugging the non-random parts of utilities (1)-(3) into (4) for each type $i = H, L$ of population, the proportion of that population choosing each option should satisfy

$$r_{\text{SP}}^i = \frac{\frac{(C_s/d_{\text{SP}})^{\alpha_i}}{(1+q_I+q)^\gamma}}{1 + \frac{(C_0/d_0)^{\alpha_i}}{(1+q_I)^\gamma} + \frac{(C_s/d_{\text{SP}})^{\alpha_i}}{(1+q_I+q)^\gamma}}, \quad (5)$$

$$r_0^i = \frac{\frac{(C_0/d_0)^{\alpha_i}}{(1+q_I)^\gamma}}{1 + \frac{(C_0/d_0)^{\alpha_i}}{(1+q_I)^\gamma} + \frac{(C_s/d_{\text{SP}})^{\alpha_i}}{(1+q_I+q)^\gamma}}, \quad (6)$$

$$r_N^i = \frac{1}{1 + \frac{(C_0/d_0)^{\alpha_i}}{(1+q_I)^\gamma} + \frac{(C_s/d_{\text{SP}})^{\alpha_i}}{(1+q_I+q)^\gamma}}, \quad (7)$$

where the total demand mass on each choice can be expressed from the choices of each population:

$$\begin{cases} d_{\text{SP}} &= \theta_H r_{\text{SP}}^H + (1 - \theta_H) r_{\text{SP}}^L \\ d_0 &= \theta_H r_0^H + (1 - \theta_H) r_0^L \\ d_N &= \theta_H r_N^H + (1 - \theta_H) r_N^L. \end{cases} \quad (8)$$

Indeed, the demand of type $i \in \{H, L\}$ users for service $j \in \{\text{SP}, 0, N\}$ is simply

$$d_j^i = r_j^i \theta_i. \quad (9)$$

Note that the previous expressions do not directly provide us with the repartition of users, since those repartitions appear on the right-hand sides through congestion effects. To determine the distribution, we need to consider the concept of *equilibrium* because users' choices affect the utilities of all other users (and thus, their subsequent choices). A user equilibrium is a fixed point solution of the system (5)–(7), representing a *stable* distribution of choices where no user has an interest to switch options.

3.3 Order of decisions

We assume that decisions are taken at different time scales and observed by subsequent players, and that decision makers are able to anticipate the reaction of subsequent players to their decisions. In other words, we assume that the interactions form a Stackelberg (or leader-follower) game [13].

1. At the largest time scale, the ISP chooses a pricing function $p(\cdot)$ for capacity sold to the CP, and a price q_I for the basic service. Its objective is to maximize its total revenue, resulting from the SP and user decisions:

$$R_{\text{ISP}} := (d_{\text{SP}} + d_0)q_I + p(C_s). \quad (10)$$

2. At a smaller time scale, the SP observes the pricing function $p(\cdot)$ and decides which amount C_s of capacity to reserve (at a price $p(C_s)$) to offer its premium service on a

slice, and what extra price q to charge for that service. We also treat that actor as revenue-oriented, i.e., trying to maximize

$$R_{\text{SP}} = d_{\text{SP}}q - p(C_s).$$

3. At the smallest time scale, users observe prices and the capacities C_s and $C - C_s$, and adapt to the services and prices that are offered (and also to the congestion levels), their selfish utility-maximizing choices being summarized by the system (5)–(8).

To analyze such a game, we use the well-known *backward induction* method, that consists in solving each stage of the game, starting from the last (smallest-scale) one, by keeping the decision variables of larger-scale stages as generic and using the solutions found for smaller-scale stages.

4 Game analysis

In this section, we carry out the analysis of the three-stage game defined previously. Following the backward induction method, we first focus on user reactions when ISP and SP decisions are made, then focus on SP decisions for given choices of the ISP, and finally compute the optimal decisions for the ISP.

Note that the complexity of the mathematical model leads to expressions that do not allow us to reach closed-form expressions for the decision variables. For that reason, we often resort to numerical computations to illustrate the main phenomena that can occur.

4.1 User equilibrium: existence

We first establish that the system (5)–(8) on user repartition over the three possible choice has a solution.

Proposition 1. *For any splitting $(C_s, C - C_s)$ of the ISP capacity into the two slices/services, and any nonnegative price profile (q, q_I) , the discrete-choice model leading to the system (5)–(8) has a solution $(r_{\text{SP}}^H, r_0^H, r_N^H, r_{\text{SP}}^L, r_0^L, r_N^L)$. We will call it a user equilibrium.*

Proof. Let $D := \{(x_H, y_H, z_H, x_L, y_L, z_L) \in \mathbb{R}^{+6} : x_H + y_H + z_H = 1, x_L + y_L + z_L = 1\}$. Consider the function $g : D \mapsto D$ that associates to each 6-uplet $(x_H, y_H, z_H, x_L, y_L, z_L) \in D$ the 6-uplet $(r_{\text{SP}}^H, r_0^H, r_N^H, r_{\text{SP}}^L, r_0^L, r_N^L) \in D$ obtained by applying first (8) then (5), (6) and (7). That function is continuous, and since D is compact and convex it has a fixed point in D , meaning that a solution exists. \square

In all our numerical experiments, the user equilibrium will be obtained by determining the fixed point of the system (5)–(8).

4.2 Quantifying how “good” an outcome is: User Welfare

We quantify user welfare with respect to the “no-connectivity” reference, in which each user would choose option N : user welfare UW is then the aggregated difference, over all the user population, of the utility they get with their choice minus the utility that option N would yield. Mathematically, since each type- i user with $i \in \{H, L\}$ selects their best option, this gives

$$UW = \sum_{i \in \{H, L\}} \theta_i \mathbb{E} [\max(u_{\text{SP}, i} - u_{N, i}, u_{0, i} - u_{N, i}, 0)] = \sum_{i \in \{H, L\}} \theta_i \int_{z=0}^{\infty} \mathbb{P}(Z_i \geq z) dz$$

with $Z_i = \max(u_{\text{SP}, i} - u_{N, i}, u_{0, i} - u_{N, i}, 0)$.

For a given $z > 0$,

$$\begin{aligned} \mathbb{P}(Z_i \leq z) &= \mathbb{P}(\{u_{\text{SP}, i} - u_{N, i} \leq z\} \cap \{u_{0, i} - u_{N, i} \leq z\}) \\ &= \mathbb{P}(u_{N, i} \geq \max(u_{\text{SP}, i} - z, u_{0, i} - z)) \\ &= \frac{1}{1 + e^{-z} \left(\frac{(C_0^i)^{\alpha_i}}{(1+qI)^\gamma} + \frac{(C_s^i)^{\alpha_i}}{(1+qI+q)^\gamma} \right)}, \end{aligned}$$

where the last equality stems from the interpretation of $u_{N, i} \geq \max(u_{\text{SP}, i} - z, u_{0, i} - z)$ in the context of discrete choice, as a user preferring option N over the two others if their payoff is amputated by z .

Therefore, with the (temporary) notation $A_i := \frac{(C_0^i)^{\alpha_i}}{(1+qI)^\gamma} + \frac{(C_s^i)^{\alpha_i}}{(1+qI+q)^\gamma}$,

we have $UW = \sum_{i \in \{H,L\}} \theta_i \int_{z=0}^{\infty} 1 - \frac{1}{1+e^{-z}A_i} dz = \sum_{i \in \{H,L\}} \theta_i \ln(1 + A_i)$, hence the expression

$$UW = \sum_{i \in \{H,L\}} \theta_i \ln \left(1 + \frac{(C_0/d_0)^{\alpha_i}}{(1+q_I)^\gamma} + \frac{(C_s/d_{SP})^{\alpha_i}}{(1+q_I+q)^\gamma} \right). \quad (11)$$

4.3 Decisions of the Service Provider (SP)

Now that the user equilibrium can be determined as a consequence of all parameters, we consider the decisions that the SP can make, regarding the price for the premium service it offers and the amount of capacity C_s to allocate for that service, following the order of decisions described in Section 3.3.

4.3.1 Setting the premium service price q

Recall that users subscribing to the premium service perceive a total price $q_I + q$, the first part going to the ISP and the second one to the SP.

Figure 1 displays the evolution of the SP revenue from subscription (ignoring the price paid for the capacity) when the SP price q varies, for the parameter values summarized in Table 1. (The values have been arbitrarily chosen; our goal is to illustrate that a maximum exists.)

C	θ_H	α_H	α_L	γ	C_s	q_I
10	0.4	2	1.5	4	5	5

Table 1: Parameters used in our numerical experiments (the two last ones are later chosen to maximize a given objective)

Maximizing the objective plotted in Figure 1 leads to the price that a revenue-oriented SP would choose once the capacity C_s is fixed. For the chosen parameters, the figure exhibits a unique maximum: the objective increases at the beginning as small price values only slightly affect demand, and decreases after a point, when the negative effect on demand of a price increase starts exceeding the per-subscriber gain. The uniqueness of the maximum has been observed in all our experiments.

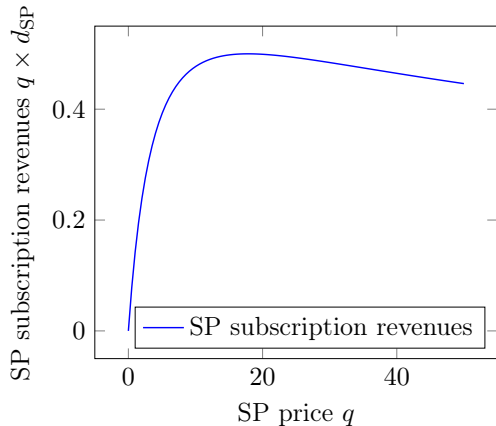


Figure 1: SP subscription revenues when q varies

4.3.2 Choosing what capacity C_s to acquire for the premium service

Having (numerically) computed the premium service price q as described in the previous subsection for any premium service capacity C_s , we now seek the revenue-maximizing C_s to obtain the pair (q, C_s) that a revenue-driven SP would choose.

Remember that the SP utility is its revenue

$$R_{\text{SP}} = d_{\text{SP}}q - p(C_s). \quad (12)$$

In Figure 2, we display the evolution of the SP utility as per (12) when varying the slice capacity C_s and with the corresponding revenue-maximizing price q , in the case when that capacity is charged a price $p(C_s) = aC_s^b$, with $a = 0.16$ and $b = 2$. This way, we can determine the optimal capacity that would be rented by the SP. Again, we can observe a unique revenue-maximizing value of C_s .

4.4 ISP decision(s): subscription price q_I (and possibly charging function $p(\cdot)$)

We now focus on the remaining last decision-maker, the ISP, who is playing first but is studied last since playing anticipatively, using the optimized values determined in the previous subsections. Remark that there are several possibilities for the choice of the charging function

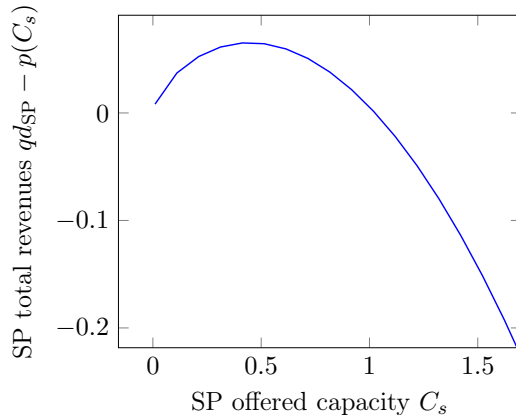


Figure 2: SP total revenues when C_s varies (at the revenue-maximizing price q)

$p(\cdot)$ for the slice: it may be imposed by a regulator (e.g., with the objective of maximizing social welfare), or chosen by the ISP to maximize revenue. An in-between option could be that the regulator imposes some constraints on that function, but leaves some degrees of freedom to the ISP. To be able to treat different cases, we first analyze the choice of the subscription price q_I for a given function $p(\cdot)$, again using the results from the previous sections regarding the subsequent decisions of the SP and users.

4.4.1 ISP choice of the basic subscription price q_I

For the charging function $p(C_s) = aC_s^b$, with $a = 0.16$ and $b = 2$, we display in Figure 3 the utility of the ISP, that stems from subscriptions (users choosing the basic or premium service) and from renting the capacity C_s (chosen by the SP and priced accordingly, as described previously). We again observe an increasing starting trend followed by a decreasing one, hence a unique revenue-maximizing value of the price q_I . We also display the impact on user welfare, that decreases as the ISP increases its subscription price q_I . To highlight the impacts of that decision variable, we also display in Figure 4 the corresponding SP revenue-maximizing choices of the premium capacity C_s and price q .

Note that for the displayed numerical example, the SP-chosen capacity C_s has also a peak value when q_I varies, for a value of q_I below the one maximizing ISP revenue. Also, we can observe that the SP-chosen price q increases linearly with q_I , and is approximately three times larger than the basic service price q_I , hence a premium service about four times

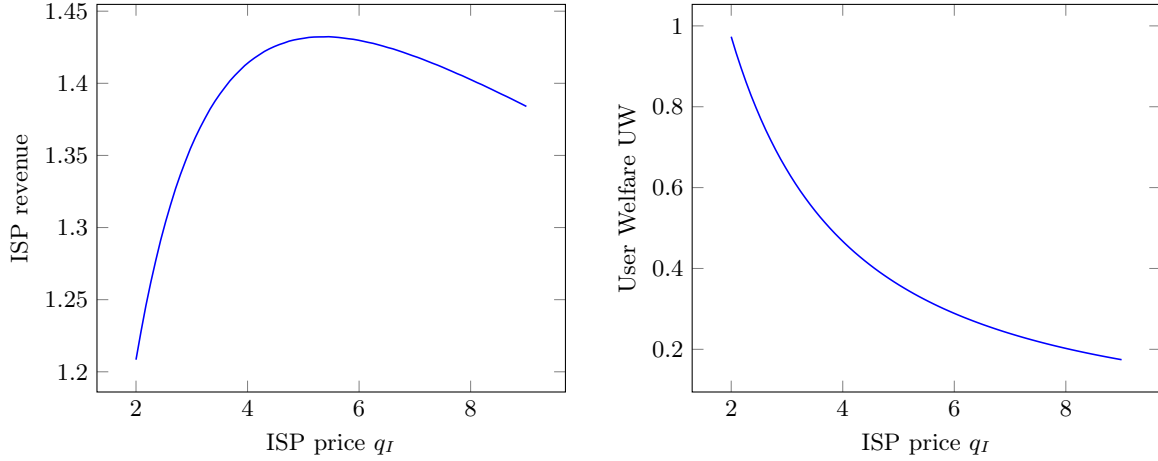


Figure 3: ISP revenue and corresponding user welfare when varying the subscription price q_I

more expensive than the basic one. Figure 5 then shows the repartition of demands at the

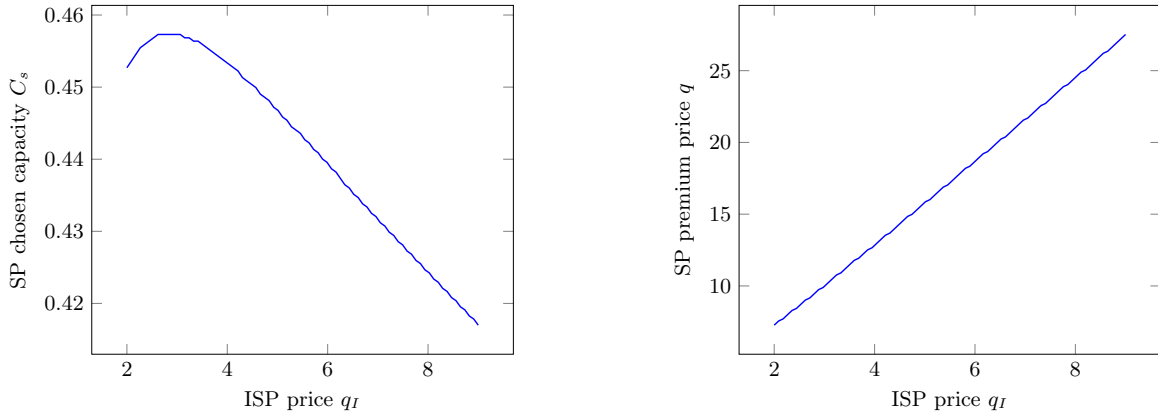


Figure 4: SP chosen capacity C_s and price q when the ISP subscription price q_I varies

corresponding equilibrium, and the (perceived) qualities of the basic and premium services – the values $\alpha_i \ln\left(\frac{C-C_s}{d_0}\right)$ and $\alpha_i \ln\left(\frac{C_s}{d_{SP}}\right)$ respectively – for each user type $i \in \{L, H\}$. This illustrates the range of variations users can experience with a change in q_I . For our example, as expected, an increasing q_I leads to decreasing masses of subscribers for both the basic and premium services, for each type. Subscriptions to the premium service are low in all cases, but strictly positive. With decreasing demand (and congestion), perceived qualities increase, with the premium quality remaining above the basic one. At the price q_I maximizing the ISP revenue (about $q_I = 5.5$), the ratio between premium and basic qualities is around 1.2; from

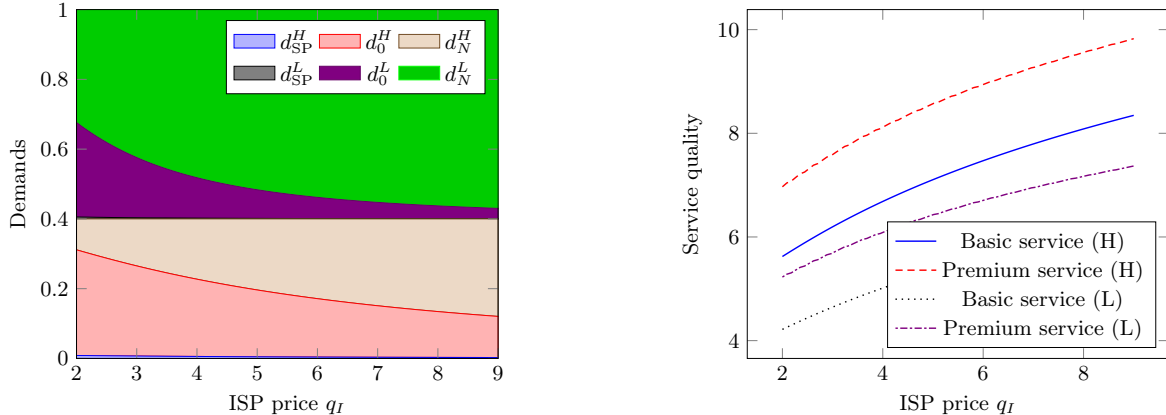


Figure 5: Demands (*left*), and basic and premium service qualities (*right*) when q_I varies, for optimal SP decisions for C_s and q .

our model that ratio is the same for both user types.

Section 6 will compare several scenarios on the freedom for the ISP to choose function $p(\cdot)$ parameters, corresponding to different levels of regulation.

5 Comparisons with an integrated ISP/SP, and with the neutral case

We propose in this section two other possible scenarios, that can be studied numerically with the same method as the one discussed so far. Those scenarios are simpler to analyze so we do not detail the resolution, but we provide comparisons with the reference scenario (with an SP independent from the ISP). For that reference scenario, we also vary the form of the pricing function for the “premium” slice.

5.1 The “vertical integration” case

This situation refers to the case when the SP and ISP are controlled by the same entity, that therefore plays on all the levers we mentioned (the basic price q_I and premium upgrade q , the capacity C_s) to maximize the total revenue

$$R_{\text{Integ}} = R_{\text{ISP}} + R_{\text{SP}} = (d_{\text{SP}} + d_0)q_I + d_{\text{SP}}q. \quad (13)$$

In particular, in that situation the capacity pricing function $p(\cdot)$ is irrelevant, since those possible payments would stay within the integrated entity.

The order of decisions, still analyzed by backward induction, is: i) at the largest time scale, the ISP chooses a price q_I , the amount C_s for the premium service on a slice and the corresponding extra price q to charge for that service in order to maximize (13); ii) users adapt to the services and prices that are offered according to (5)–(7).

5.2 The neutral case

In this paper, we refer to the neutral situation as service differentiation being forbidden, so that only one slice (type of service) is allowed. The goal is to see what slicing brings with respect to a service without differentiation. This comparison is crucial in the context of the network neutrality debate [6]. As a result, in the neutral scenario there is no SP offering a premium service, and only two options—namely to subscribe to the service (option 0) or not (option N)—are available to users of each type. Following the previous assumptions and derivations, a user equilibrium would be of the form $(r_0^H, r_N^H, r_0^L, r_N^L)$, with

$$r_0^i = \frac{\left(\frac{C}{\theta_H r_0^H + \theta_L r_0^L}\right)^{\alpha_i} / q_I^\gamma}{1 + \left(\frac{C}{\theta_H r_0^H + \theta_L r_0^L}\right)^{\alpha_i} / q_I^\gamma}, \quad (14)$$

$$r_N^i = \frac{1}{1 + \left(\frac{C}{\theta_H r_0^H + \theta_L r_0^L}\right)^{\alpha_i} / q_I^\gamma}. \quad (15)$$

As before, demand masses per type for each option satisfy (9).

Then the order of decisions simplifies to: i) the ISP decides q_I and ii) users choose to subscribe or not according to (14) and (15).

As with the 3-choice situation in Equations (5)–(7), for any price $q_I > 0$ there is a user equilibrium. The ISP can then optimize by playing on q_I , anticipating the user equilibrium, in order to maximize its revenue.

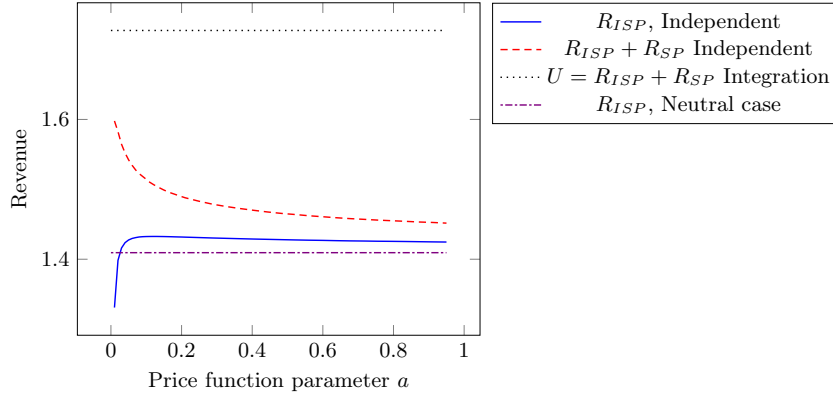


Figure 6: ISP revenue R_{ISP} (plus the SP revenue in some cases) when the parameter a of the capacity pricing function varies

5.3 Comparison

We compare the three situations (independent SP, integrated ISP-SP, neutral) when the capacity pricing function $p(\cdot)$ varies: more specifically, we keep the form $p(C_s) = aC_s^b$, with $b = 2$, and vary the constant multiplicative parameter a .

Figure 6 shows the ISP revenue in terms of a , also adding in some cases the SP revenue for comparison purposes and for the integrated scenario (hence two curves are displayed for the independent situation). We observe a parameter value maximizing the ISP revenue in (10), here $a = 0.12$ for our set of parameters. The revenue in the integrated case in (13) (when maximizing prices in this context) is larger than the combined ISP and SP revenue in the independent case, which is always larger than the revenue (of the ISP being alone) in the neutral case. Focusing on the ISP revenue only, in this case too, except for very small values of a (less than 0.03), the independent case yields a larger value than the neutral case: it is better to leave high-demanding customers to an SP and get only a compensation for that to focus on the “less demanding” ones, than to try to get a maximal benefit through a unique price for all customers. In summary, unless forced to almost give its capacity for free to the SP, the ISP is better off allowing slicing. Note also the slow decrease of the ISP revenue when a increases after reaching its maximizing value 0.12. Figure 7 displays the corresponding selected capacity C_s for each a . We see a decreasing behavior: the higher the price, the lower the capacity acquired by the SP. At the optimal value $a = 0.12$, the optimal C_s is 0.552,

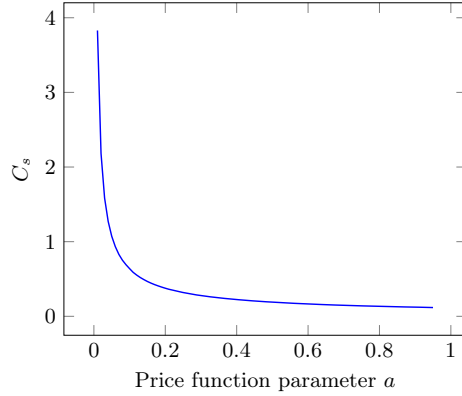


Figure 7: Chosen capacity C_s by the service provider in terms of capacity pricing a

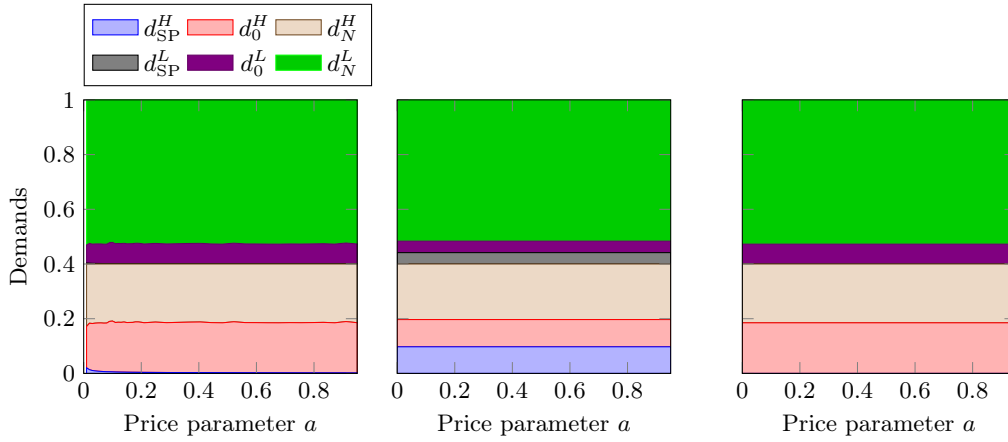


Figure 8: From left to right: demands when a varies at equilibrium, for the independent, integrated, and neutral cases.

that is 5.52% of the total capacity, a limited amount, at least with our set of parameters. The repartition of demand is shown in Figure 8. The proportion of users asking for the premium service is limited in the independent case (even hardly visible on the figure since the population of type H selecting that service decreases from 2% to 0.1% of the full population, while it decreases from 0.3% to 0.06% for type L). Only the integrated scenario yields a visible proportion of premium users.

6 Comparison with regulated-prices situations

To widen our comparison basis, in addition to the *unregulated* situation where the ISP is free to decide the values of q_I and of the parameter a to maximize its revenue, we consider two

other situations where regulation occurs. Instead of just forbidding service differentiation as in the neutral case, we consider here that some prices are regulated, in the sense that they are chosen so as to maximize the resulting user welfare. This type of restriction has already been applied in other contexts. For example in France, the price the main operator Orange is allowed to sell its capacity to competing providers is determined by the regulator¹. We consider the following options:

- in the situation we will label as “*weakly regulated*”, the regulator selects the parameter a of the capacity price function $p(\cdot)$;
- in the “*fully regulated*” case, the regulator additionally fixes the price q_I for the basic service. Note that this situation may not be realistic, since the ISP—not controlling its service price—could end up with very low revenues, not enough to cover its infrastructure, operation and maintenance costs.

Table 2 displays the outputs for all the five scenarios evoked so far, namely the (unregulated) independent ISP-SP, an integrated ISP-SP, and the regulated situations of neutrality (no premium service), weak and full regulation. The results are given again for the parameters described in Table 1.

	a	q_I	q	C_s	r_{SP}^H	r_0^H	r_N^H	r_{SP}^L	r_0^L	r_N^L	R_{SP}	R_{ISP}	UW
Unregulated	0.12	5.32	16.83	0.55	0.01	0.45	0.53	0.00	0.12	0.87	0.070	1.430	0.330
Vertical Integ.	–	6.15	0.00	4.92	0.24	0.25	0.51	0.07	0.07	0.86	–	1.73	0.361
Neutral	–	5.47	–	–	–	0.46	0.54	–	0.12	0.88	–	1.409	0.326
Fully regulated	0.95	4.0	14.5	0.12	0.01	0.57	0.43	0.0	0.2	0.8	0.03	1.422	0.47
Weakly regulated	0.1	5.14	16.37	0.64	0.01	0.46	0.52	0.00	0.13	0.87	0.080	1.430	0.350

Table 2: Comparison of outputs according to the regulation scenario with parameters described in Table 1

Note that with the parameter values we chose, the ISP is indifferent between the unregulated and weakly regulated (a chosen to maximise UW) settings, while the SP slightly prefers the weakly regulated setting. Both situations are also close in terms of user welfare, still with a slight advantage for weak regulation, and both of them would be preferred to imposing neutrality (no premium service allowed). If possible, a fully regulated setting (with a and q_I

¹<https://en.arcep.fr/news/press-releases/view/n/arcep-sets-the-regulatory-framework-for-orange-fixed-networks-for-the-next-three-years.html>

regulated) yields a significantly better user welfare: it fixes a relatively high price a diminishing significantly the SP revenue (reduced by more than 50%) with respect to other situations, but with a very limited impact on the ISP. The increased UW comes from the lower subscription price q_I ; it may be seen as a relevant alternative by a regulator. Comparing vertical integration and the unregulated case, vertical integration is somewhat surprisingly (slightly) beneficial to users, not only to the SP+ISP federation.

7 Conclusions

This paper proposes a model to analyze the economic implications of the 5G slicing paradigm. In particular, the focus is on the allocation of radio resource, as its scarcity creates limits on the performance of slices.

Our numerical results can be interpreted as arguing in favor of the concept of slicing, as user welfare is larger in all slicing scenarios than in a neutral setting, where no service differentiation is allowed. However, except in the extreme situation of a fully regulated network (including prices of the basic service), the user welfare gains remain small in relative value. As regards the ISP, introducing slicing has little impact too, the largest one being in the vertical integration case.

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