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# An Economic Analysis of 5G Network Slicing and the Impact of Regulation

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**Abstract**—Network slicing is a key component of 5G-and-beyond networks, requiring to define a business model for resource allocation. We consider a model with a Service Provider (SP) that may purchase a slice in a wireless network, in order to 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. One optimization problem for the SP is the choice of how much resource to allocate to that slice. We also compare with the case of a unique “pipe” (no premium service) and with the case of vertical integration to evaluate the impact of slicing on all actors and identify the “best” economic scenario.

**Index Terms**—Network slicing, 5G networks, ressource allocation, pricing

## I. 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 requirements 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 [21].

Introducing slicing capabilities involves, however, designing an associated business model: if no charge is imposed, then there is no incentive for users or applications to limit a slice “size” and reserve useless resources at the expense of others. It

is also an opportunity for network operators, that we will refer to as Internet Service Providers (ISP), to get more value out of the transport of services, by giving them more control on their network (being a part of the service delivery value chain), instead of just being the “paper boy” who distributes content and just getting infrastructure rental revenues determined by national regulators [12].

Remark also that network slicing, even if technically and economically appealing, faces issues due to its apparent contradiction with the network neutrality principles [10], that are “bypassed” by the introduction of so-called specialized services. This is discussed in the literature [5], [17], [20]; the interest of slicing with respect to a neutral situation will be analyzed in this paper when actors maximize their own interest.

We propose here a new model for network slicing involving an ISP, a service provider (SP) interested in buying a slice, and end users sensitive to price and quality of service who choose 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 [11], [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. It also allows to encompass two other scenarios, namely *i*) the case without slicing and *ii*)

the case of vertical integration where the SP and ISP are the same entity, in order to make comparisons and to investigate whether a scenario has a major impact on providers, users and society as a whole. We can then make suggestions towards an “efficient” management of the network.

Briefly, the numerical investigations carried out from our model show that user welfare is slightly improved in all slicing scenarios with respect to a neutral (no differentiation) scenario, the only real gain occurring when prices are fully regulated, an unlikely scenario since almost nullifying the ISP revenue.

The remainder of the paper is organized as follows. Section II reviews the related work and highlights the contribution. Section III 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 IV analyzes the game by backward induction. Section V 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 VI additionally analyzes what happens when the slice prices are fully or partially regulated. Finally Section VII concludes and proposes extensions of the present work.

## II. 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 [8] 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. based on the Kelly mechanism [7] 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 [18] 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 [19], are proposed. Another, this time revenue-maximizing, auction is proposed in [6] where the resource is separated in chunks. Paper [22] on the other hand presents a more specific auction mechanism designed for Mobile Virtual Network Operators (MVNOs), but easily transcribed 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.

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.

## III. MODEL

### A. 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 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. 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  $R_{SP} = -p(C_s) + d_{SP}q$ , with  $q$  the unit service price charged to users, and  $d_{SP}$  the user demand for the premium service.

- **User** choices among the available options (basic service, premium service, no service) are modeled with an attraction-based approach that allows us to express the proportion of users making each choice [9]. 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.

As a result, 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

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

where  $\alpha_{\text{SP}}$  represents the sensitivity to the throughput per service unit  $\frac{C_s}{d_{\text{SP}}}$ , with  $d_{\text{SP}}$  the total demand for that service;  $\gamma$  is the user sensitivity to prices, and  $\kappa_{\text{SP}}$  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].

Another choice for a user, 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:

$$u_0 = \alpha_0 \ln \left( \frac{C - C_s}{d_0} \right) - \gamma \ln(1 + q_I) + \kappa_0,$$

where  $\alpha_0$  is the sensitivity to the throughput per service unit  $\frac{C - C_s}{d_0}$ , 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  $\kappa_0$  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 utility except for the user-specific (subjective) term, leading to

$$u_N = 0 + \kappa_N.$$

Each user selects the option with the largest utility. Given the probabilistic expressions, we end up with proportions (i.e., probabilities) over each choice.

### B. User equilibrium

With such a model, and assuming without loss of generality a total user mass of 1, selfish choices from all users would lead to the following repartition over the three options, with  $C_0 := C - C_s$  to simplify notations [1], [9]:

$$d_{\text{SP}} = \frac{\frac{(C_s/d_{\text{SP}})^{\alpha_{\text{SP}}}}{(1+q_I+q)^\gamma}}{1 + \frac{(C_0/d_0)^{\alpha_0}}{(1+q_I)^\gamma} + \frac{(C_s/d_{\text{SP}})^{\alpha_{\text{SP}}}}{(1+q_I+q)^\gamma}}, \quad (1)$$

$$d_0 = \frac{\frac{(C_0/d_0)^{\alpha_0}}{(1+q_I)^\gamma}}{1 + \frac{(C_0/d_0)^{\alpha_0}}{(1+q_I)^\gamma} + \frac{(C_s/d_{\text{SP}})^{\alpha_{\text{SP}}}}{(1+q_I+q)^\gamma}}, \quad (2)$$

$$d_N = \frac{1}{1 + \frac{(C_0/d_0)^{\alpha_0}}{(1+q_I)^\gamma} + \frac{(C_s/d_{\text{SP}})^{\alpha_{\text{SP}}}}{(1+q_I+q)^\gamma}}. \quad (3)$$

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 (1)–(3), representing a *stable* distribution of choices where no user has an interest to switch options.

### C. 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:

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

- 2) At a smaller time scale, the SP decides which amount  $C_s$  of capacity to reserve (at a price  $p(C_s)$ ) to offer its premium service on a slice, and at 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 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 (1)–(3).

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.

## IV. 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.

### A. User equilibrium: existence and uniqueness

We first establish that the system (1)–(3) defines a unique user repartition over the three possible choices, and show how to compute it.

**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 (1)–(3) has a unique solution  $(d_{\text{SP}}, d_0, d_N)$ , which we will call a user equilibrium.*

*Proof.*

- *Existence:* Let  $D_3 := \{(x, y, z) \in \mathbb{R}^+ : x + y + z = 1\}$ . Then the function  $g : D_3 \mapsto D_3$  that associates to each triplet

$(d_{\text{SP}}, d_0, d_N) \in D_3$  the triplet defined by right-hand terms of (1), (2) and (3) respectively is continuous, and since  $D_3$  is compact and convex it has a fixed point in  $D_3$ .

• *Uniqueness:* A solution  $(d_{\text{SP}}, d_0, d_N)$  has to satisfy  $\frac{d_{\text{SP}}^{1+\alpha_{\text{SP}}}}{d_0^{1+\alpha_0}} = \frac{C_s^{\alpha_{\text{SP}}/(1+q_I+q)}\gamma}{C_0^{\alpha_0/(1+q_I)}\gamma}$ , thus

$$d_0 = \left( d_{\text{SP}}^{1+\alpha_{\text{SP}}} \frac{C_0^{\alpha_0}}{C_s^{\alpha_{\text{SP}}}} (1+q/(1+q_I))^\gamma \right)^{\frac{1}{1+\alpha_0}}. \quad (4)$$

Similarly, we must have  $\frac{d_{\text{SP}}^{1+\alpha_{\text{SP}}}}{d_N} = C_s^{\alpha_{\text{SP}}/(1+q_I+q)}\gamma$ , hence

$$d_N = d_{\text{SP}}^{1+\alpha_{\text{SP}}} \frac{(1+q_I+q)^\gamma}{C_s^{\alpha_{\text{SP}}}}. \quad (5)$$

Now as the right-hand terms of (1), (2) and (3) add up to 1, any solution satisfies  $d_{\text{SP}} + d_0 + d_N = 1$ , and thus

$$d_{\text{SP}} + \left( d_{\text{SP}}^{1+\alpha_{\text{SP}}} \frac{C_0^{\alpha_0}}{C_s^{\alpha_{\text{SP}}}} (1+q/(1+q_I))^\gamma \right)^{\frac{1}{1+\alpha_0}} + d_{\text{SP}}^{1+\alpha_{\text{SP}}} \frac{(1+q_I+q)^\gamma}{C_s^{\alpha_{\text{SP}}}} = 1. \quad (6)$$

The left-hand term in (6) is continuous in  $d_{\text{SP}}$ , and strictly increasing from  $\mathbb{R}^+$  to  $\mathbb{R}^+$ . Hence (6) has at most one solution, and exactly one (that is in  $D_3$ ) from the existence proof. The values  $d_0$  and  $d_N$  are then also unique from (4) and (5).  $\square$

Note that the proof of Proposition 1 provides a solution to rapidly compute numerically the user equilibrium: Equation (6) can easily be solved by dichotomy to find  $d_{\text{SP}}$ , and (4) and (5) then directly give  $d_0$  and  $d_N$ .

### B. 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 user selects their best option, this gives  $UW = \mathbb{E}[\max(u_{\text{SP}} - u_N, u_0 - u_N, 0)] = \int_{z=0}^{\infty} \mathbb{P}(Z \geq z) dz$  with  $Z = \max(u_{\text{SP}} - u_N, u_0 - u_N, 0)$ .

For a given  $z > 0$ ,

$$\begin{aligned} \mathbb{P}(Z \leq z) &= \mathbb{P}(\{u_{\text{SP}} - u_N \leq z\} \cap \{u_0 - u_N \leq z\}) \\ &= \mathbb{P}(u_N \geq \max(u_{\text{SP}} - z, u_0 - z)) \\ &= \frac{1}{1 + e^{-z} \left( \frac{(C_0/d_0)^{\alpha_0}}{(1+q_I)^\gamma} + \frac{(C_s/d_{\text{SP}})^{\alpha_{\text{SP}}}}{(1+q_I+q)^\gamma} \right)}, \end{aligned}$$

where the last equality stems from the interpretation of  $u_N \geq \max(u_{\text{SP}} - z, u_0 - z)$  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  $A := \frac{(C_0/d_0)^{\alpha_0}}{(1+q_I)^\gamma} + \frac{(C_s/d_{\text{SP}})^{\alpha_{\text{SP}}}}{(1+q_I+q)^\gamma}$ , we have  $UW = \int_{z=0}^{\infty} 1 - \frac{1}{1+e^{-z}A} dz = \ln(1+A)$ , hence the expression

$$UW = \ln \left( 1 + \frac{(C_0/d_0)^{\alpha_0}}{(1+q_I)^\gamma} + \frac{(C_s/d_{\text{SP}})^{\alpha_{\text{SP}}}}{(1+q_I+q)^\gamma} \right). \quad (7)$$

### C. 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 III-C.

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 I.

$C$	$\alpha_{\text{SP}}$	$\alpha_0$	$\gamma$	$C_s$	$q_I$
10	2	2	4	0.5	5

Table I

PARAMETERS USED IN OUR NUMERICAL EXPERIMENTS (THE TWO LAST ONES ARE LATER CHOSEN OPTIMALLY)

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.

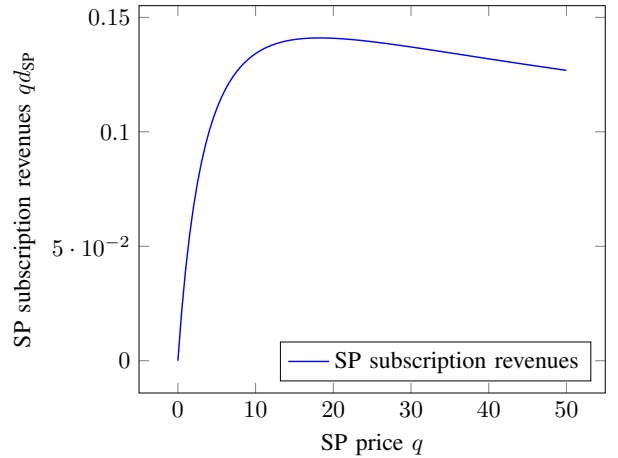


Figure 1. SP subscription revenues when  $q$  varies

2) *Choosing what capacity  $C_s$  to acquire for the premium service:* The previous subsection provides us with a (numerical) way to compute the premium service price  $q$ . We use that revenue-maximizing price when varying the premium service capacity  $C_s$  to obtain the pair  $(q, C_s)$  that a revenue-driven SP would choose.

Since the SP utility is its revenue

$$R_{\text{SP}} = d_{\text{SP}} q - p(C_s), \quad (8)$$

the result will of course depend on the pricing function  $p(\cdot)$  applied by the ISP. In Figure 2, we display the evolution of

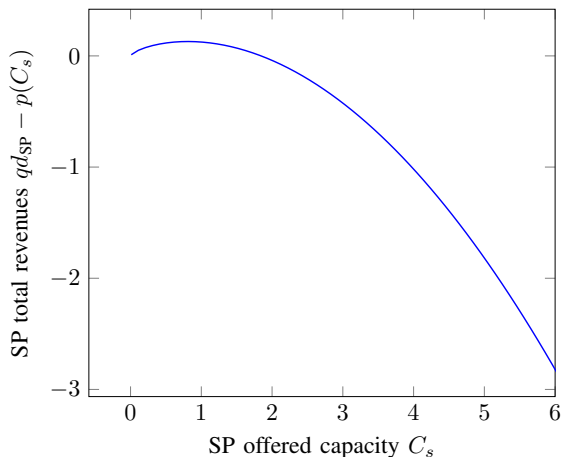


Figure 2. SP total revenues when  $C_s$  varies (at the revenue-maximizing price  $q$ )

the SP utility as per (8) 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  $a = 0.1$  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  $C_s$ .

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

The last decision-maker to study (and also the first one to play) is the ISP.

Depending on the scenario we want to consider, the charging function  $p(\cdot)$  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.

1) *ISP choice of the basic subscription price  $q_I$* : For the charging function  $p(C_s) = aC_s^b$ , with  $a = 0.1$  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  $q_I$ . 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 (at least) for the displayed numerical example, the SP-chosen capacity  $C_s$  behaves very similarly to the ISP revenue, so that  $q_I$  being optimally chosen by the ISP corresponds to the SP buying a large capacity  $C_s$ . Also, we can observe that the SP-chosen price  $q$  is approximately three times larger than the

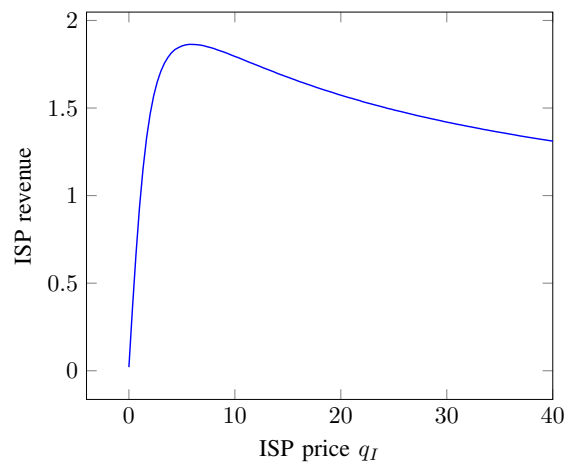


Figure 3. ISP revenue when varying the subscription price  $q_I$

basic service price  $q_I$ , hence a premium service about four times more expensive than the basic one. Figure 5 then shows the repartition of demands at the corresponding equilibrium, and the qualities of the basic and premium services, illustrating the range of variations they can experience with a change in  $q_I$ . For our example, for the price  $q_I$  maximizing the ISP revenue (about  $q_I = 1.3$ ), the premium quality is around 4, versus a basic quality of 1.5, a large difference due to the (also large) price difference deterring many users from the premium service, hence very little congestion.

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

## V. 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.

### A. 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

$$R_{\text{Integ}} = R_{\text{ISP}} + R_{\text{SP}} = (d_{\text{SP}} + d_0)q_I + d_{\text{SP}}q. \quad (9)$$

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

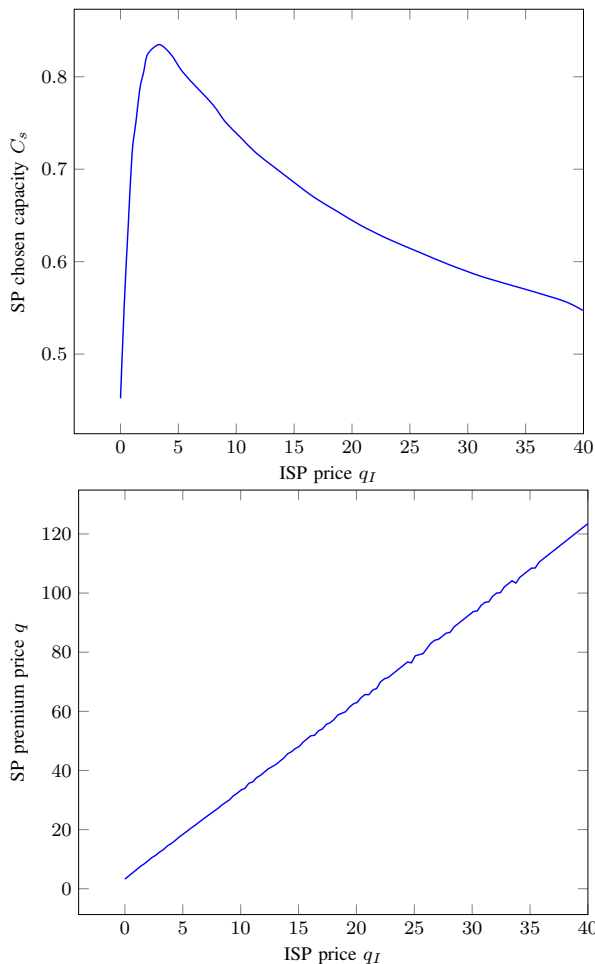


Figure 4. SP chosen capacity  $C_s$  and price  $q$  when the ISP subscription price  $q_I$  varies

to maximize (9); ii) users adapt to the services and prices that are offered according to (1)–(3).

### B. 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, particularly in the context where it is opposed by network neutrality proponents [5]. As a result, there is no SP offering a premium service, and only two options are available to users, namely to subscribe to the service (option 0) or not (option  $N$ ). Following the previous assumptions and derivations, a user equilibrium would be of the form  $(d_0, d_N)$ , with

$$d_0 = \frac{(C/d_0)^{\alpha_0}/q_I^{\gamma}}{1 + (C/d_0)^{\alpha_0}/q_I^{\gamma}}, \quad (10)$$

$$d_N = \frac{1}{1 + (C/d_0)^{\alpha_0}/q_I^{\gamma}}. \quad (11)$$

Then the order of decisions simplifies to: i) the ISP decides  $q_I$  and ii) users choose to subscribe or not according to (10) and (11).

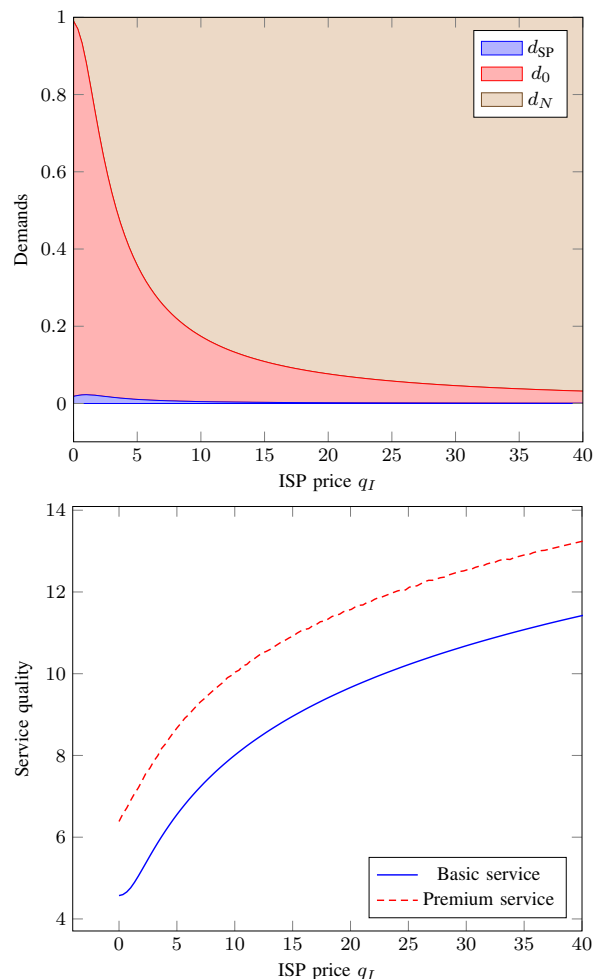


Figure 5. Demands (*left*), and basic and premium service qualities (*right*) when  $q_I$  varies, for optimal SP decisions for  $C_s$  and  $q$ .

As with the 3-choice situation in Equations (1)–(3), for any price  $q_I > 0$  there is a unique user equilibrium. The ISP can then optimize by playing on  $q_I$ , anticipating the user equilibrium, in order to maximize its revenue.

### C. 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 values of user welfare in terms of  $a$ . The implemented strategy seems to have a limited impact on UW, all values being slightly different but close. It can be highlighted that UW is about 5% larger in the integrated scenario than in the independent case. To better understand what happens, the repartition of demand is shown in Figure 7. The proportion of users asking for the premium service is limited, explaining the small differences on UW. It may be due to the values of  $\alpha_{SP}$  and  $\alpha_0$  in Table I: having a larger  $\alpha_{SP}$  with respect to  $\alpha_0$  would probably mean more demand for the premium service.

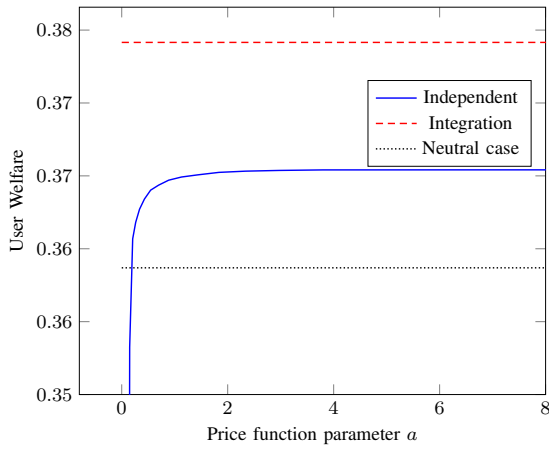


Figure 6. User Welfare at equilibrium when the parameter  $a$  of the capacity pricing function varies

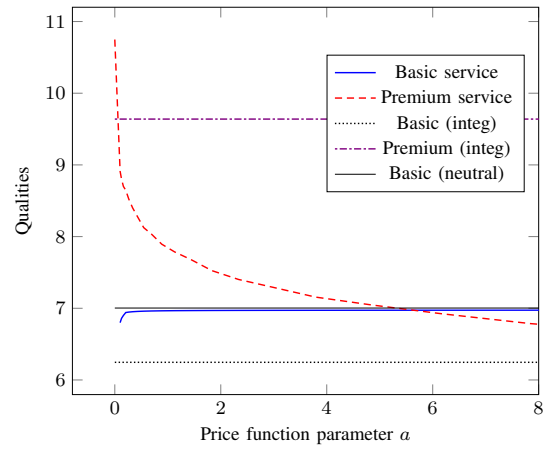


Figure 8. Service qualities at equilibrium when the parameter  $a$  of the capacity pricing function varies

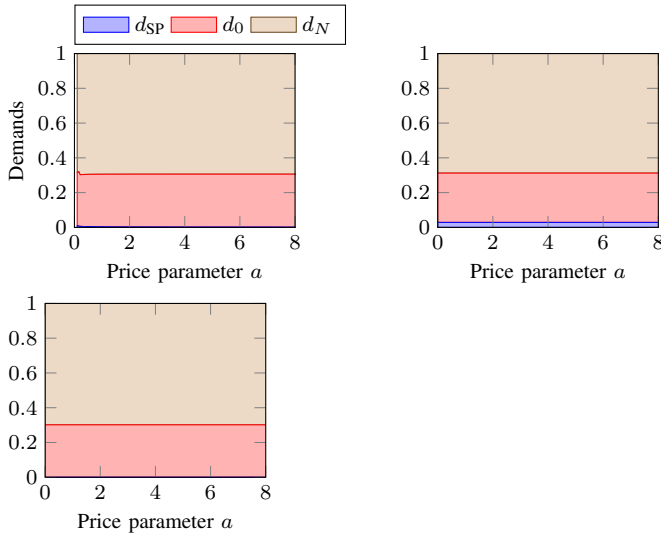


Figure 7. Demands when  $a$  varies at equilibrium, for the independent, integrated, and neutral cases, respectively.

Figure 8 shows the corresponding service qualities. Note that the quality of the premium service may be below that of the basic service: in such a case there can still be users choosing that option ( $d_{SP} > 0$ ) due to the utility model including a “random” component, but their mass is extremely small, as illustrated in Figure 7. Surprisingly though, increasing the price (that is,  $a$ ) decreases the quality: it is due to a corresponding decreased capacity  $C_s$  allocated to the premium service. The basic service quality is the largest in the neutral situation, but the value in the independent-slicing scenario is close. Finally, an integrated SP-ISP entity creates larger service quality differences, thereby incentivizing more users to select the premium service. We do not show the revenues when  $a$  varies, as the impact is small, yielding almost-flat curves.

## VI. COMPARISON WITH REGULATED-PRICES SITUATIONS

To widen our comparison basis, in addition to the *unregulated* situation where the ISP is free to decide  $q_I$  and 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 regulator<sup>1</sup>. 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 9 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 I.

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 unregulated setting. Both situations are also close in terms of user welfare, and both of them would be preferred to imposing neutrality (no premium service allowed). If possible, a fully regulated setting (with  $a$  and  $q_I$  regulated) yields a significantly better user welfare, although through offering the

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



	$a$	$q_I$	$q$	$C_s$	$d_{SP}$	$d_0$	$d_N$	$R_{SP}$	$R_{ISP}$	UW
Unregulated	5.60	6.08	21.11	0.04	0.00	0.30	0.70	0.017	1.843	0.361
Vertical Integ.	–	4.95	18.67	3.56	0.03	0.28	0.69	–	2.08	0.374
Neutral	–	6.11	–	–	–	0.30	0.70	–	1.841	0.359
Fully regulated	2.98	0.0	3.03	0.03	0.0	0.99	0.01	0.01	0.01	4.64
Weakly regulated	7.3	5.69	20.70	0.03	0.00	0.31	0.69	0.015	1.843	0.369

Figure 9. Comparison of outputs according to the regulation scenario with parameters described in Table I

basic service for free, an assumption that may be unrealistic since the ISP revenue would be close to zero. Comparing vertical integration and the unregulated case, vertical integration is somewhat surprisingly (slightly) beneficial to users, not only to the SP+ISP federation.

## VII. 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 (less than 5%). As regards the ISP, introducing slicing has little impact too, the largest one being in the vertical integration case. But those impacts may be larger by refining the model, which can be carried out in future work. In particular, instead of having user heterogeneity in quality sensitivity represented only through a random variable in the discrete-choice model, we would like to explicitly consider two types of users with fixed (or a different range of) quality sensitivity, so as to represent different types of 5G services with different requirements.

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