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Unleashing the potential of QoS-aware pricing within licensed shared access framework

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Abstract

We present a techno-economic analysis of a cellular market that operates within the licensed shared access (LSA) framework, consisting of a mobile network operator (MNO) that leases spectrum to a number of programme making and special events (PMSE) users. The MNO offers two quality-of-service (QoS) classes (high and low), differentiating the price based on the QoS class. The key question that we address is whether and to which extent the MNO has incentive to adopt this form of QoS-aware pricing. After getting some promising insights from the analysis of two case studies, we propose a general methodology. The first step is to model the parameters that are controlled by each PMSE user: (i) the way to choose between the two QoS classes and (ii) the available budget per QoS class. The second step is to compute the maximum revenue of the MNO. Our analysis reveals that the MNO can always tune the prices so as to maximise its revenue for the scenario where all users belong to the high QoS class. This is a consistent result throughout our study that holds for any considered set of user-controlled parameters and of technical parameters. We conclude that the adoption of QoS-aware pricing in an LSA market generates a tussle between the MNO and the regulator. The MNO has incentive to support fewer users but with high QoS and charge them more, which is not aligned with the regulator's goal for social welfare maximisation.

Keywords: Techno-economics, Mobile network operators, Programme making and special events

1 Introduction and related work

Licensed shared access (LSA) [2] has been adopted in Europe as a promising paradigm to dynamically share licensed spectrum between different networks and technologies. LSA proposes a two-tier approach where the initial target use case considered mobile network operators (MNOs) leasing spectrum in the 2.3–2.4 GHz band from incumbent technologies like programme making and special events (PMSE) [3]. However, recent initiatives from industry and spectrum regulators have proposed a symmetric use case, where PMSE users could lease spectrum from MNOs, targeting reliable short-term use of spectrum for concerts, conferences, etc. [4].

Though the adoption of LSA brings significant benefits from a technical perspective, a number of business challenges arise for the key stakeholders of the market (i.e., regulator, incumbent spectrum user, and LSA licensee). These include the MNO's costs of additional infrastructure and the required modifications of the existing systems to support and manage the sharing procedure, as well as the license fees [5]. Thus, the stakeholders must perform a techno-economic analysis in order to assess whether LSA is worth the investment. However, business research on LSA is scarce [6–8] and focuses on the qualitative domain, without offering quantitative results on whether LSA schemes are techno-economically attractive.

The work closest to ours is [9], where an MNO that operates under the LSA framework leases spectrum to a number of PMSE users that belong to two distinct quality-of-service (QoS) classes, admitting either low or high QoS requirements. As in [9], we study scenarios where all users have either high or low QoS requirements, as well as mixed QoS requirements (i.e., some users have low and some users have high QoS requirements). We extend the approach of [9], aiming at unleashing the potential of QoS-aware pricing in this LSA market, where we adopt price differentiation based on the QoS class. Our key contributions are the following. From the perspective of the PMSE users, we model the behaviour of the users regarding how they choose between the two QoS classes, as well as their available budgets for the two QoS classes. Through this process, we are able to predict the distribution of the users between the two QoS classes for each possible combination of considered prices.

From the perspective of the MNO, we first present two case studies where we compare the revenue of the three QoS scenarios when the MNO applies QoS-aware pricing (i) without offering any discounts, (ii) offering a discount to some of the users with Q_H, and (iii) offering a discount to some of the users with Q_H and some of the users with Q_L. The results from these case studies highlight the potential after the application of QoS-aware pricing. We then identify the prices that correspond to the maximum revenue that can be achieved for each QoS scenario. A consistent result arises independently of (i) the distribution of the budgets, (ii) the way that the users choose between the QoS classes, and (iii) the values of the technical parameters. The MNO can always tune the prices so that the maximum revenue for the high QoS scenario is the highest, followed by the mixed QoS scenario and finally by the low QoS scenario. This result highlights the potential of QoS-aware pricing for the MNO, since the MNO has motivation to sacrifice some of the users with low QoS in order to support more users with high QoS and charge them more. This is also interesting from a regulatory point of view, since we identify a constant tussle in the LSA market, where the goal of the MNO (i.e., revenue maximisation) is not aligned with the goal of the market regulator (i.e., social welfare maximisation). Finally, we quantify the impact of the budget parameters on the revenue of the QoS scenarios, providing insights for which markets have the potential to be more profitable for the MNO.

2 Methods

We first summarise the techno-economic input from [9] that we are going to use for our analysis. Then, we introduce our extensions. We assume a single provider market with one MNO and N PMSE users that are interested in leasing spectrum from the unique MNO. Consistent with one of the business models in [4], the PMSE users also utilise the network infrastructure of the MNOs. Furthermore, the PMSE users are classified into two distinct QoS classes: there are at most N_L PMSE users with low QoS requirements (e.g., audio speech applications) and at most N_H PMSE users with high QoS requirements (e.g., high definition audio productions). We are interested in analysing from a techno-economic point of view the following three QoS scenarios:

- *Low QoS scenario*: The MNO can support at most N_L users, where all of them have the same low QoS requirements Q_L.
- *High QoS scenario*: The MNO can support at most N_H users, where all of them have the same high QoS requirements Q_H.
- *Mixed QoS scenario*: The MNO supports users with mixed QoS requirements, i.e., at most $N_{L,M}$ users with Q_L and at most $N_{H,M}$ users with Q_H.

Given the maximum number of supported PMSE users for the three QoS scenarios, the goal of the MNO is to define a pricing policy and choose the scenario that will maximise its revenue. Among the four pricing policies that have been considered in [9], we apply QoS-aware pricing, where the differentiation in the price is based on the QoS class that each user belongs to [10]. Depending on the assumptions and the model, QoS-aware pricing may maximise e.g. the revenue of the MNO or the social welfare [11, 12].

We adopt a type of QoS-aware pricing which corresponds to an application of the *second degree of price discrimination* [13]. In this form of discrimination, there are at least two distinct prices, which correspond to at least two different types of services. Any customer who wants the same type of service will pay the same price. In our case, we propose that the discrimination is based on the QoS class that each PMSE user belongs to; each user that targets Q_L pays $P_L \in [P_{L,\min}, P_{L,\max}]$, whereas each user that targets Q_H pays P_H. We also define parameter $K = \frac{P_H}{P_L}$ which is always above 1. Then, the revenue of the MNO for each of the three QoS scenarios is:

$$\text{Low QoS Scenario: } N_L P_L, \tag{1}$$

$$\text{High QoS Scenario: } N_H P_H = N_H K P_L, \tag{2}$$

$$\text{Mixed QoS Scenario: } N_{L,M} P_L + N_{H,M} P_H = N_{L,M} P_L + N_{H,M} K P_L. \tag{3}$$

Clearly, the scenario that maximises the MNO's revenue can be computed by the following formula: $\max\{N_L, N_H K, N_{L,M} + N_{H,M} K\}$.

In [9], there has been an extensive study of the revenue for the three QoS scenarios. For different values of the technical parameters including carrier frequency *f*, propagation environment, base station (BS) transmit power level, and bandwidth, the maximum number of supported PMSE users for the three QoS scenarios has been computed. Then, the revenue after the application of QoS-aware pricing has been estimated for a fixed value of P_L and a range of values of P_H. A key assumption during the whole analysis was that the MNO always serves the maximum number of users that can be technically supported.

We generalise this study towards the following two directions. First, we introduce an additional degree of freedom studying markets with different values of P_L. Second, we relax the assumption that the market always performs at its maximum capacity by proposing a methodology to compute the exact number of PMSE users that will be admitted in each QoS scenario. In order to do so, we need to model the behaviour of the users.

Initially, we need to model how a user chooses between the two QoS classes. Therefore, we introduce a metric w that quantifies the preference of each user i for each QoS class by weighing the importance that the user gives to the price and the QoS. For the high QoS class, w is defined as follows:

$$w_{H,i} = a_i \frac{P_L}{P_L + P_H} + (1 - a_i) \frac{Q_H}{Q_L + Q_H},$$

where the user-specific parameter a_i follows a uniform distribution in (0,1). When a_i is above 0.5, user i considers as the most important factor the price that it has to pay, otherwise the most decisive factor is the QoS that it gets. We note that we use fractions for a relative comparison of the two factors that influence the decision of the user, which is why w also ranges between 0 and 1.

Similarly, for the low QoS class, w is defined as:

$$w_{L,i} = a_i \frac{P_H}{P_L + P_H} + (1 - a_i) \frac{Q_L}{Q_L + Q_H}.$$

Note that $w_{H,i} + w_{L,i} = 1$, meaning that each user i needs to compute just one of them. If $w_{H,i}$ is higher than 0.5, then user i prefers the high QoS class. Otherwise, it prefers the low QoS class.

Another aspect that was not modelled in [9] is the user's available budget for each QoS class. Though we are not aware of specific studies for the distribution of the budgets of the PMSE users, we expect that it follows a (variation of the) normal distribution. This is in accordance with adjacent telecommunication markets [13]. More specifically, we model the distribution of the budget for the low QoS B_L as a truncated normal distribution with minimum value $P_{L,\min} = \$10$ [14]. We need a minimum value, otherwise a user can never get access to this QoS class, so it is not of interest for this market. We study 6 cases for B_L, where the mean $\mu_L = \{0.5, 0.7, 0.9\} P_{L,\max}$ and the standard deviation $\sigma_L = \{0.2, 0.4\} P_{L,\max}$, with $P_{L,\max} = \$120$ [14].

Then, we model the distribution of the budget for the high QoS B_H as a truncated normal distribution with minimum value B_L. The motivation for this minimum threshold is that the user's budget for the high QoS class should be at least equal to its budget for the low QoS class. For B_H, we also consider 6 cases, where the mean $\mu_H = \{0.2, 0.4, 0.6\} \frac{Q_H}{Q_L} B_L$ and the standard deviation $\sigma_H = \{0.2, 0.4\} \frac{Q_H}{Q_L} B_L$. The quantity $\frac{Q_H}{Q_L} B_L$ is used as a benchmark, since, as we know from adjacent markets [13], a typical user is expected to be willing to spend at most $\frac{Q_H}{Q_L}$ times more to get the class Q_H instead of the class Q_L. Moreover, since the budget of the users for more expensive services is expected to be tighter, the coefficients of μ_H are typically lower than the ones of μ_L.

2.1 Maximum Number of PMSE Users

Table 1 summarises the values of the technical parameters from [9] used to estimate the maximum number of PMSE users that can be technically supported. Each PMSE user has either high or low QoS requirements. We define the QoS requirements in terms of the target application-layer throughput R, where high QoS and low QoS correspond to 4.61 Mbps and 150 kbps, respectively. These values are consistent with the highest and lowest PMSE audio throughput requirements in [4, 15], where low throughput values

Table 1 PMSE user QoS requirements and technical parameters

Parameter	Value		
	Low QoS Scenario	**High QoS Scenario**	**Mixed QoS Scenario**
PMSE user QoS requirements as Application-layer throughput R	150 kbps [4, 15]	4.61 Mbps [4, 15]	4.61 Mbps for 50% of the users in the high QoS scenario and 150 kbps for other users
bandwidth C	20 MHz [17]		
carrier frequency f	800, 2600, 3800 MHz [17]		
BS transmit power T	30 dBm [17, 18] (same for all BSs)		
propagation environment	indoor, outdoor		

Table 2 Max. number of users that can be supported for the three QoS scenarios for the different values of the technical parameters

Frequency, environment	Scenario			
	Low QoS	**High QoS**	**Mixed QoS**	
	Users N_L	**Users** N_H	**Users** $N_{L,M}$	**Users** $N_{H,M}$
f=800 MHz, indoor	65	6	21	3
f=800 MHz, outdoor	7	2	4	1
f=2600 MHz, indoor	36	4	13	2
f=2600 MHz, outdoor	31	4	12	2
f=3800 MHz, indoor	37	4	13	2
f=3800 MHz, outdoor	33	4	12	2

correspond to audio speech applications, while high throughput values are required for high definition audio productions [16]. Based on these values of the technical parameters, Table 2 summarises from [9] the maximum number of users that can be supported for the three QoS scenarios. Since the number of users for the carrier frequencies of 2600 MHz and 3800 MHz are quite similar, we analyse only three cases: (i) 800 MHz for the indoor propagation environment, (ii) 800 MHz for the outdoor propagation environment, and (iii) 3800 MHz for the indoor propagation environment.

3 Revenue analysis: a case study

In this section, we illustrate the evolution of the revenue for the three QoS scenarios for the example of the carrier frequency f=3800 MHz and the indoor propagation environment. As a first step, the MNO announces publicly the maximum number of available slots for the two QoS classes as well as the corresponding prices P_L and P_H for each QoS class. Then, we consider a first-come, first-served mechanism, where each user gets admitted automatically to the QoS class of its preference provided that the following two conditions hold: (i) it can afford to pay the price that the MNO has announced and (ii) the MNO has not reached the maximum number of PMSE users that it can support for this QoS class.

In this section, we consider that the users follow a so-called *non-strict* version for the choice of the QoS class. In this non-strict version, a user initially applies for getting access to the QoS class that it prefers more based on the value of the weighted metric w.

If the user does not get access to the QoS class of its first choice, then it applies for the other QoS class and it gets admitted provided that the previously mentioned conditions hold. In the following sections, we also consider a *strict* version for the choice of the QoS class, where each user applies for only one QoS class, i.e., the one that corresponds to the highest value of the weighted metric w.

For our simulations, we consider 1000 markets. Each market consists of 41 PMSE users so that, provided that all of them have the necessary budget to pay for the prices P_L and P_H, the maximum number of supported users can be admitted (i.e., either $N_L = 37$, or $N_H = 4$). Each user chooses its parameter a_i from a uniform distribution in (0,1), whereas the parameters of the distribution of the budgets B_L and B_H are set as follows: $\mu_L = 0.7P_{L,\max}$, $\sigma_L = 0.4P_{L,\max}$, $\mu_H = 0.4\frac{Q_H}{Q_L}B_L$, $\sigma_H = 0.2\frac{Q_H}{Q_L}B_L$ with $P_{L,\max} = \$120$ [14]. Moreover, we study four values of P_L, corresponding to 30, 60, 90, and 120 $ for 48-h access [14]. For a given P_L, we apply QoS-aware pricing where $P_H = KP_L$, with parameter $K \in \{2, 3, \ldots, \left\lfloor \frac{Q_H}{Q_L} \right\rfloor = 30\}$.

Figure 1 shows the evolution of the revenue for the three QoS scenarios for the four values of P_L. Each subfigure corresponds to the revenue as a function of parameter K, for a given P_L. Therefore, for each QoS scenario, we simulate 360 combinations of P_L and P_H. For each combination of P_L and P_H, we plot the mean revenue along with their corresponding error bars for each QoS scenario after the simulation of 1000 markets. As we notice from Fig. 1a, when parameter K is below 7, the low QoS scenario generates the highest revenue. This is justified since the price differentiation between Q_H and Q_L is small enough to not overcome the difference between the actual number of users that are supported for Q_H and Q_L. For higher values of K, the high QoS scenario generates the highest revenue, followed by the mixed QoS scenario. Also, the revenue for both the high QoS and the mixed QoS scenario increases linearly with K. This is expected from the corresponding equations (2) and (3) provided that the number of users N_H and $N_{H,M}$ does not change with K. Finally, for the low QoS scenario, the revenue does not change with K, so any fluctuation is due to changes in the number of users.

Figure 1b shows the revenue for $P_L = \$60$, where we notice some differences in the trends. First, though P_L was doubled compared to Fig. 1a, the revenue for the low QoS scenario was not doubled. This means that the budget B_L of some of the users is below $60 and, therefore, they cannot afford to pay for this QoS class. Due to this, the high QoS scenario generates the highest revenue starting with a smaller value of K (it is for $K > 6$, whereas for $P_L = \$30$ it was for $K > 7$). Moreover, for high values of K, the revenue for the high QoS scenario starts increasing sub-linearly and then it decreases. This is again due to budget constraints, this time for the budget B_H. The trend of a sub-linear increase is also noticed for the mixed QoS scenario, though it starts for higher values of K compared to the high QoS scenario. This is expected since, for the mixed QoS scenario, the maximum number of users with high QoS that can be admitted is 2 instead of 4 for the high QoS scenario (see Table 2). Therefore, for higher values of K, it is easier to find 2 instead of 4 users with Q_H.

Figure 1c,d verify the above-mentioned trends. The revenue for the low QoS scenario starts decreasing as P_L increases further to $90 and $120, since many users cannot afford to pay these prices. The message learnt for the MNO is that, for the low QoS scenario, a high price does not lead to high revenues. Due to this, the high QoS scenario generates

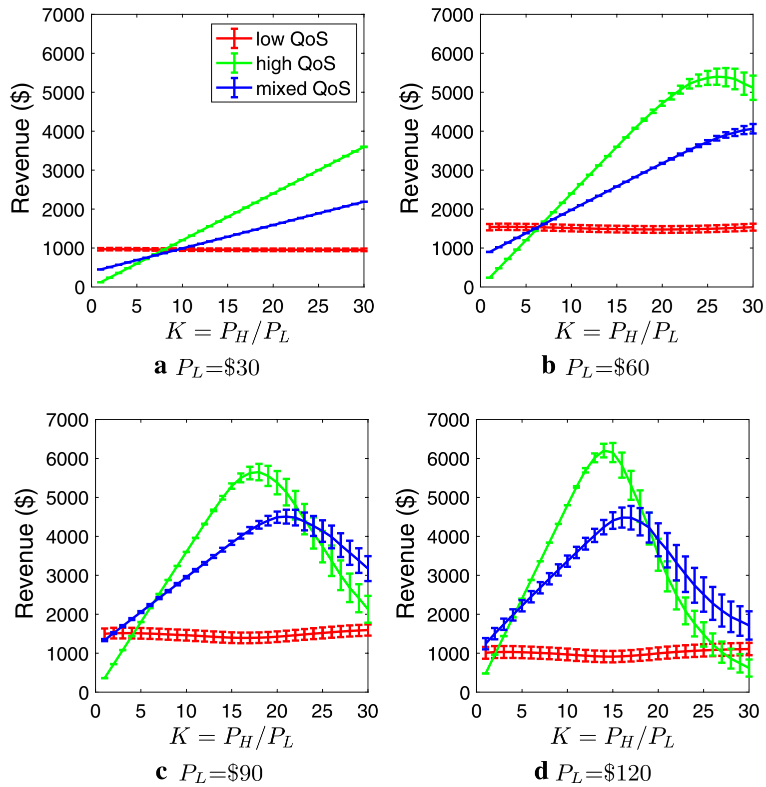

Fig. 1 Evolution of the revenue for the three QoS scenarios. Technical parameters: carrier frequency f=3800 MHz and indoor propagation environment. Parameters of the distribution of the budgets B_L and B_H: $\mu_L = 0.7P_{L,\max}$, $\sigma_L = 0.4P_{L,\max}$, $\mu_H = 0.4\frac{Q_H}{Q_L}B_L$, $\sigma_H = 0.2\frac{Q_H}{Q_L}B_L$. The choice of the QoS class is non-strict

the highest revenue, even with very low values of K. Also, the maximum revenue for the high QoS scenario is admitted for a value of K that decreases as P_L increases. The same trends hold for the mixed QoS scenario, but with a higher value of K due to fewer users with high QoS. Due to this and a steep decrease for the revenue of the high QoS scenario, the mixed QoS scenario is the most profitable when both P_L and K are high. As a final comment, it is worth mentioning that for these values of P_L, the region close to the intersection point of the mean revenue of the two QoS scenarios corresponds to overlapping error bars, creating uncertainty on which QoS scenario generates higher revenue. However, as the difference between the mean values increases, the trend becomes clear.

4 Revenue analysis: a case study with discounts on Q_H and Q_L

In this section, we compare the revenue from the three QoS scenarios for the case where the MNO has the degree of freedom to offer discounts in order to attract some PMSE users that cannot afford the face value. One option for this discount phase is to be implemented whenever the MNO finds out that, after the deadline of the initial call for applications, some slots are still available. The MNO may then decide to discount them in order to generate additional revenue, following the first-come, first-served mechanism that we discussed in Sect. 3. Another option for the MNO is to offer this discount either voluntarily, targeting e.g. a number of users with whom there is a long-lasting partnership, or following a regulatory directive. In any case, independent of the exact motivation for the discount and its implementation details, we study the following two cases:

1 Discount on Q_H: the users that belong to the set $N_H - N_{H,M}$ will pay a discounted price $s_H P_H$.
2 Discounts on Q_H and Q_L: on top of the previous policy, we further assume that the users that belong to the set $N_L - N_{L,M}$ will pay a discounted price $s_L P_L$.

Similar to [9], for our case study we set $s_H = 0.5$, $s_L = 0.8$, whereas we choose $P_L = \$120$. Moreover, we assume that the choice of the QoS class is non-strict.

Figure 2 depicts the results for 800 MHz for the indoor propagation model, where Fig. 2a corresponds to the case where the MNO does not offer any discount, Fig. 2b corresponds to the case where the MNO offers discount on users with Q_H, whereas in Fig. 2c the MNO offers discounts for both Q_H and Q_L. The only difference between Fig. 2a and Fig. 2b is the revenue for the high QoS scenario which is lower for the latter case since some of the users with high QoS will pay 50% less than the original price. Due to this discount, the high QoS scenario generates the largest revenue only when parameter K is larger than 15, whereas in Fig. 2a this was the case for any K larger than 8. Therefore, for this set of technical parameters, the discount on users with Q_H promotes

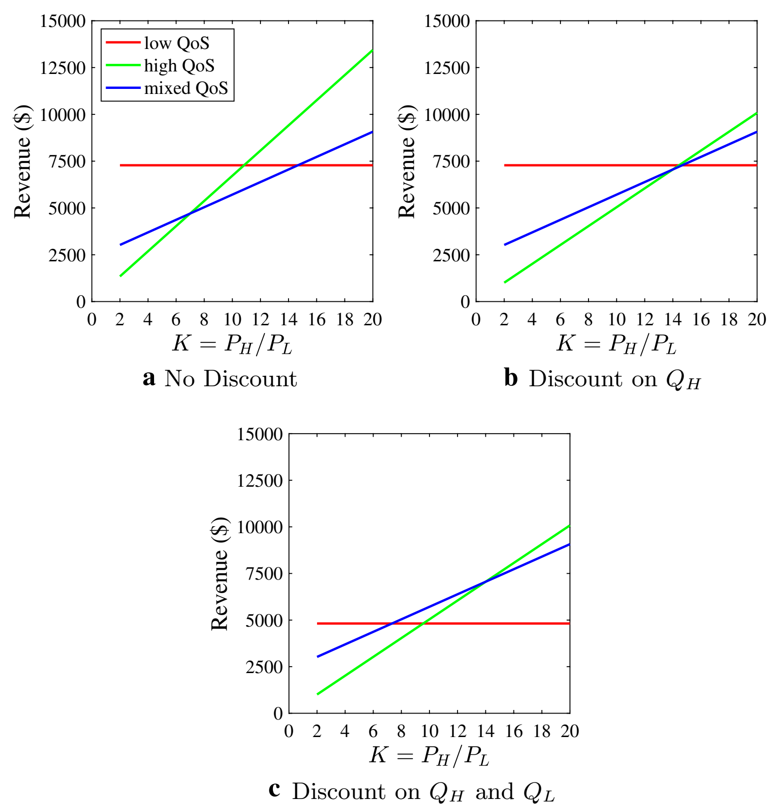

Fig. 2 Revenue for the three QoS scenarios for the cases with (i) no discount, (ii) 50% discount for $N_H - N_{H,M}$ high QoS users, (iii) discount as in (ii) along with 20% discount for $N_L - N_{L,M}$ low QoS users. Technical parameters: $f = 800$ MHz, indoor. The choice of the QoS class is non-strict

the low QoS scenario which is the winner when the level of the price discrimination between high and low QoS users (as tuned by parameter K) is large. This is not the case when the market consists of low QoS users for whom a discount is also necessary, otherwise they cannot afford the face value. In this case depicted in Fig. 2c, the revenue for both mixed and low QoS scenarios is reduced compared to Fig. 2b, making the mixed QoS scenario the winner for values of K between 8 and 13, whereas the high QoS scenario generates the largest revenue for values above 13.

Figure 3 presents the results for the same set of simulations for 800 MHz by considering this time the outdoor propagation model. We conclude that, for almost any value of parameter K, the MNO has motivation to support fewer users, adopting either the high or the mixed QoS scenario. The winner between them depends on the exact value of parameter K as well as on whether there is discount on Q_L too. This result implies that even if the market consists of PMSE users with tighter budget constraints, the MNO has motivation to prioritize the access to high QoS users, sacrificing some low QoS users.

Finally, we present in Fig. 4 the results for the same set of simulations for 3800 MHz and the indoor propagation model. For the case where the MNO does not offer any discount, when the level of the price discrimination is low, the low QoS scenario is the winner, whereas when the level of the price discrimination is high, the high QoS scenario is

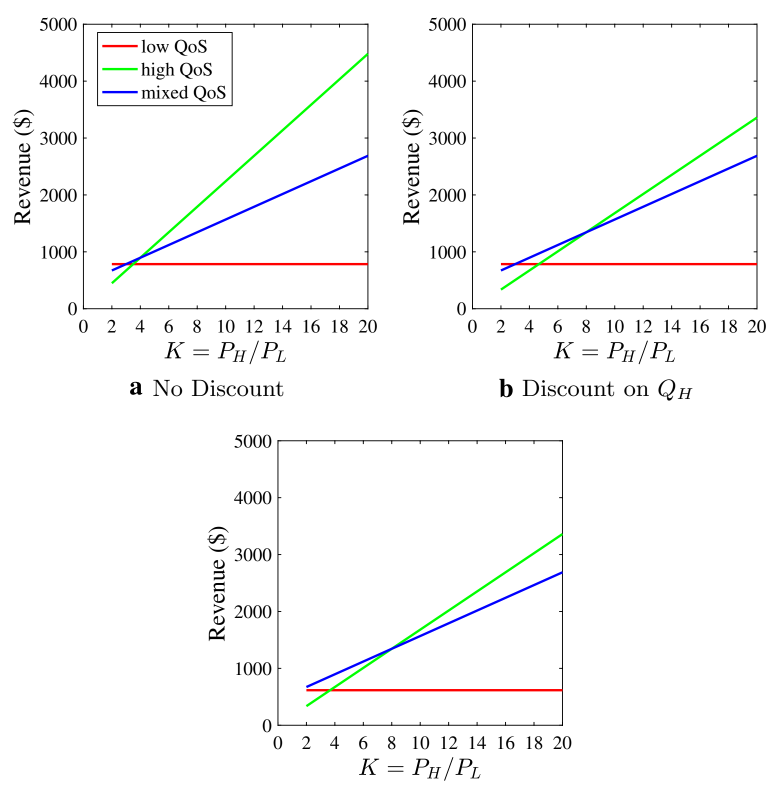

Fig. 3 Revenue for the three QoS scenarios for the cases with (i) no discount, (ii) 50% discount for $N_H - N_{H,M}$ high QoS users, (iii) discount as in (ii) along with 20% discount for $N_L - N_{L,M}$ low QoS users. Technical parameters: $f = 800$ MHz, outdoor. The choice of the QoS class is non-strict

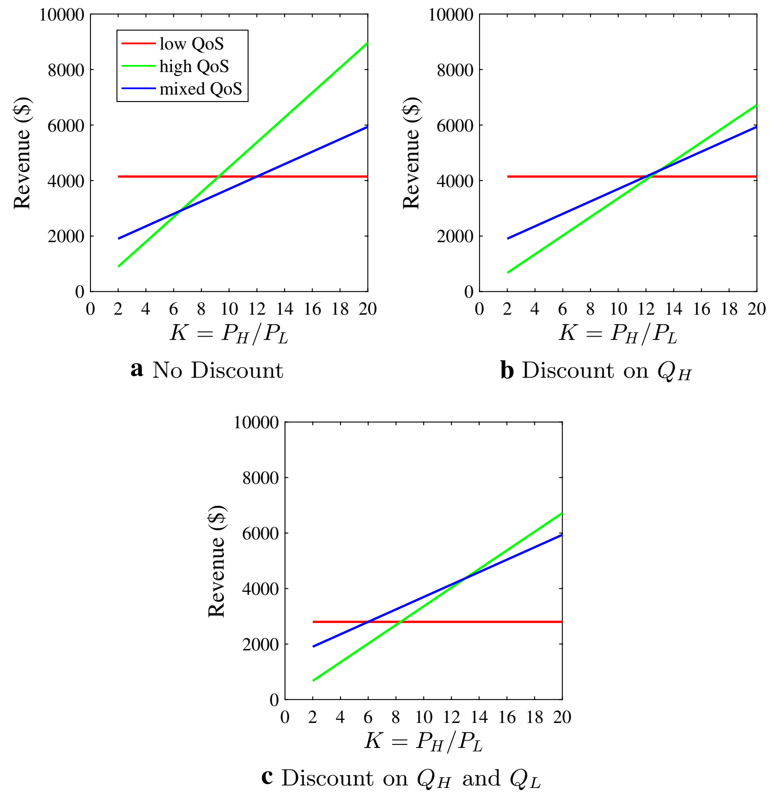

Fig. 4 Revenue for the three QoS scenarios for the cases with (i) no discount, (ii) 50% discount for $N_H - N_{H,M}$ high QoS users, (iii) discount as in (ii) along with 20% discount for $N_L - N_{L,M}$ low QoS users. Technical parameters: f=3800 MHz, indoor. The choice of the QoS class is non-strict

the winner. When the MNO offers discounts (Fig. 4b, c), we notice the same trend with 800 MHz and the indoor propagation model. When only users with high QoS get a discount, then the low QoS scenario is the winner for most values of parameter K, whereas when both QoS classes get discounts, the high QoS scenario is the winner.

The bottom line from this case study is that the potential of the QoS-aware pricing is high even when some of the PMSE users cannot afford the face value and the MNO needs to subsidize the access to its services. However, there is a joint impact of the exact level of price discrimination, the budget constraints of the users as well as the technical parameters. All these factors should be taken into account in order to identify the regions where this QoS-aware pricing policy will generate the largest revenue.

5 Revenue analysis: general results

Through the detailed analysis of the previous two case studies, we are able to compute the expected revenue of the three QoS scenarios for every possible combination of the techno-economic parameters. Though this methodology provides a fine-grained view for each case, we need to extract general conclusions. Indeed, for a given set of techno-economic parameters, the ultimate challenge for the MNO is to choose the prices P_L and P_H so that its revenue will be maximised. Therefore, we can consider this fine-grained analysis as an internal process for the MNO to compute: (i) the value of P_L that maximises its revenue for the low QoS scenario, (ii) the value of P_H, i.e., parameter K and P_L, that maximises its revenue for the high QoS scenario, and (iii) the values of P_L and P_H that maximise its revenue for the mixed QoS scenario. Then, the MNO can choose which QoS scenario maximises globally its revenue.

Though the MNO controls the technical parameters and the price, the distribution of the users' budgets as well as the users' preferences for the two QoS classes are private information. The complementary problem of how to estimate this piece of information is not addressed in this paper. However, we present a broad number of scenarios for the parameters that each user controls, so as to estimate the revenue for the three QoS scenarios under different users' behaviours. Having identified the most profitable QoS scenarios, the operator is then expected to mine the profiles of the users in order to match the general distribution of their budgets with the pricing policy that maximises its revenue.

Initially, we generalise the results of the previous section where we consider 36 budget scenarios for the distribution of the users' budgets B_L and B_H. The number of budget scenarios arises since the 4-tuple $\{\mu_L, \sigma_L, \mu_H, \sigma_H\}$ can get $3 \cdot 2 \cdot 3 \cdot 2 = 36$ possible values. Figure 5 represents the evolution of the budget distribution. We progressively update the elements of the 4-tuple in four loops, with the following order from the outermost loop to the innermost loop: (i) μ_L, (ii) σ_L, (iii) μ_H, and (iv) σ_H. Due to this, as we can see from Fig. 5a, μ_L, depicted as a red line, increases every 12 budget scenarios, remaining the same for scenarios 1–12, 13–24, and 25–36. Let us consider scenarios 1–12: due to a higher value of σ_L, scenarios 7–12 have higher upper quartiles and whiskers than scenarios 1–6. For the case of B_H (Fig. 5b), we notice that every 6 scenarios where μ_L and σ_L are fixed (i.e., scenarios 1–6, 7–12, etc.), the upper quartile increases. Moreover, the maximum upper whiskers correspond to scenarios 6, 12, etc., where B_H has the highest coefficients for μ_H and σ_H.

Figure 6 presents the maximum revenue and the corresponding values for P_L and P_H for the three QoS scenarios. As in Fig. 1, we consider the *non-strict* version for the choice of the QoS class and the results are obtained for the carrier frequency $f = 3800$ MHz and the indoor propagation environment. For all combinations of budgets B_L and B_H in Fig. 6a, the maximum revenue of the MNO is achieved for the high QoS scenario, followed by the mixed QoS scenario and then by the low QoS scenario. This result highlights the existence of a tussle for this market between the

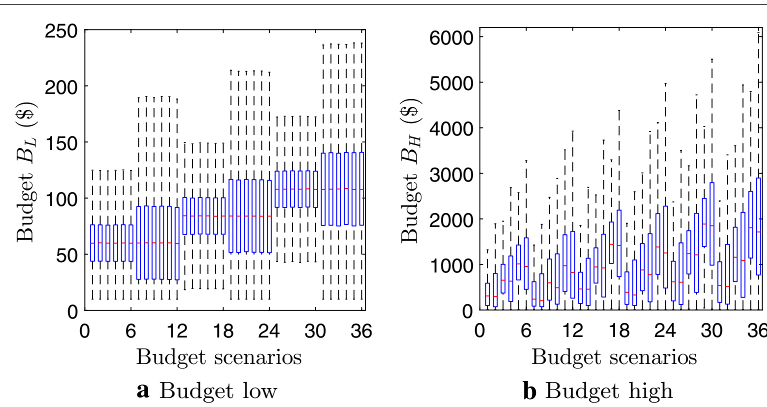

Fig. 5 Distribution of the budgets B_L and B_H

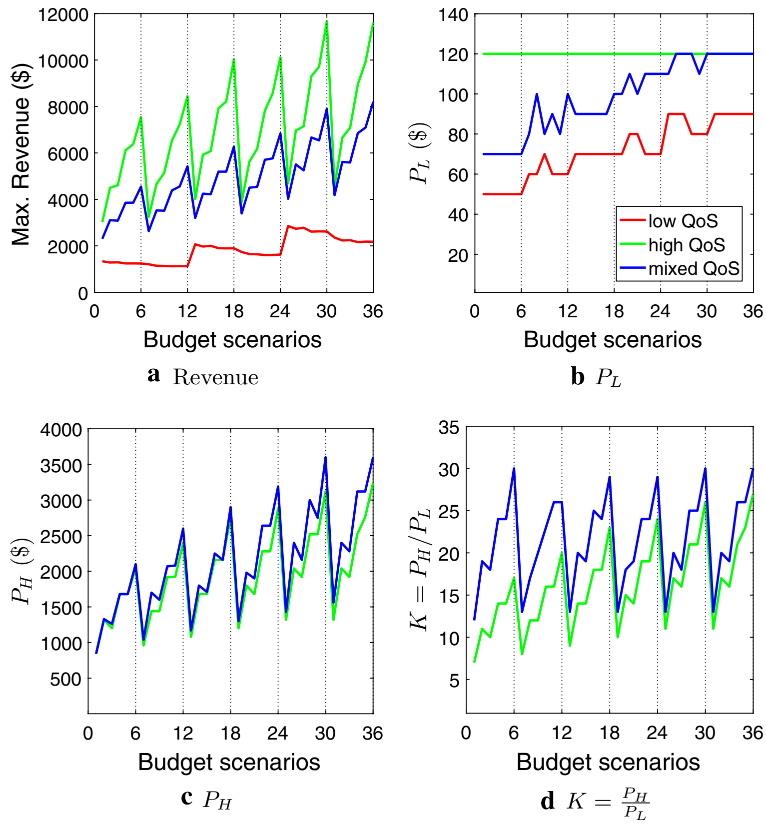

Fig. 6 Max. revenue and the corresponding values for P_L and P_H for the three QoS scenarios. Technical parameters: $f = 3800$ MHz, indoor. The choice of the QoS class is non-strict

social welfare (i.e., supporting the maximum number of PMSE users) and the revenue maximisation. Focusing on the revenue from the high QoS scenario, we notice that, for budget scenarios 1-6, the maximum is for the last scenario (scenario 6) and this trend is repeated every six scenarios. The explanation is based on the previous analysis for the distribution of the budget B_H. The same trend holds for the mixed QoS scenario, implying that the dominant component for the mixed QoS revenue is the revenue that arises from the users with Q_H. Finally, for the low QoS scenario, there is a repeating trend for budget scenarios 1–12, 13–24, and 25–36. We recall from Fig. 5a that all budget scenarios of each of these cycles correspond to the same μ_L of the budget distribution B_L. Moreover, the revenue during each cycle slightly decreases, admitting three local maxima for budget scenarios 1, 13, 25, where μ_H and σ_H have the lowest values (see Fig. 5b).

Figure 6b presents the corresponding value of P_L for which the maximum revenue for each QoS scenario is achieved. It is interesting that for the high QoS scenario, P_L is always equal to \$120, i.e., the maximum that the MNO can set throughout the study. For the mixed QoS scenario, P_L is higher than the corresponding price for the low QoS scenario. This is expected, since in the mixed QoS scenario, the MNO can admit at most 13 users with Q_L, instead of 37 users for the low QoS scenario (see Table 2). We also notice that the evolution of P_L is similar for both low and mixed

QoS scenarios, with the highest values being for budget scenarios 31–36, where μ_L and σ_L get the highest values (see Fig. 5a).

Then, we show in Fig. 6c the corresponding value of P_H. As expected, it is higher for the mixed QoS scenario where at most 2 users with Q_H can be supported than for the high QoS scenario where $N_H = 4$. Moreover, the curves follow the same trend with the revenue. Finally, Fig. 6d depicts the evolution of parameter $K = \frac{P_H}{P_L}$, where the trends are similar with the trends for P_H. Clearly, there is room for the MNO to apply higher price differentiation for the case of the mixed QoS scenario compared to the high QoS scenario. Our analysis suggests that in budget scenarios where μ_H and σ_H get the highest values, the MNO has motivation to charge the mixed QoS users with Q_H at the maximum level of price differentiation, i.e., 30 times more than the users with Q_L.

We repeat the same analysis for the *strict* preference of the QoS class, where each user has a single choice for the QoS class. Figure 7a compares the maximum revenue for the non-strict and the strict version. The conclusion that arises is that, for all QoS scenarios and all budget scenarios, the revenue is higher for the non-strict version. This is justified due to the fact that the set of revenues for the MNO for the non-strict version is a superset of the strict version: it additionally includes the revenue that each user can bring for its second QoS preference in case it has not been admitted for its first QoS preference. We identify the factors that can justify the difference in the revenue between the non-strict and the strict version, as follows.

The first one is that the number of PMSE users for the non-strict version can be higher than for the strict version. This is clearly the case for the low QoS scenario where, as we can see from Fig. 7b, there is a significant drop in the number of users with Q_L for the strict version. However, it is worth mentioning that even in the case of the non-strict version, the maximum revenue for the low QoS scenario does not coincide with the theoretical maximum of PMSE users that can be supported, which is 37. This means that either some users do not have the necessary budget B_L to pay for a particular price P_L, or it is more profitable for the MNO to support fewer users with Q_L but at a higher price. Furthermore, it is interesting to notice that, e.g., budget scenarios 1–6 correspond to a higher number of users with Q_L than scenarios 7–12. Given that these scenarios have the same mean μ_L, we conclude that the standard deviation σ_L for scenarios 1–6, which is smaller than for scenarios 7–12, is the reason for the difference in the number of users. Indeed, for the users with Q_L, it is more profitable for the MNO if the standard deviation σ_L is smaller, since, for prices P_L that are close to μ_L, more users can afford to pay for it.

The second factor is that, in the non-strict version, the MNO may have motivation to support fewer users provided that it can charge them more. This is the case with the mixed QoS scenario, where, for some budget parameters (budget scenarios 26-28), the MNO in the non-strict version prefers to support fewer users with Q_L (dark blue solid line) than in the strict version (dark blue dashed line).

We finally proceed with the results for the other two technical cases, i.e., carrier frequency $f = 800$ MHz and indoor/outdoor propagation environment. We present the maximum revenue and the corresponding number of users for the three QoS scenarios in Fig. 7c–f. As in Fig. 7a, the high QoS scenario generates always the highest revenue. This is a strong result independent of the technical parameters and the distribution of the budgets. Regarding the corresponding number of users, the two key

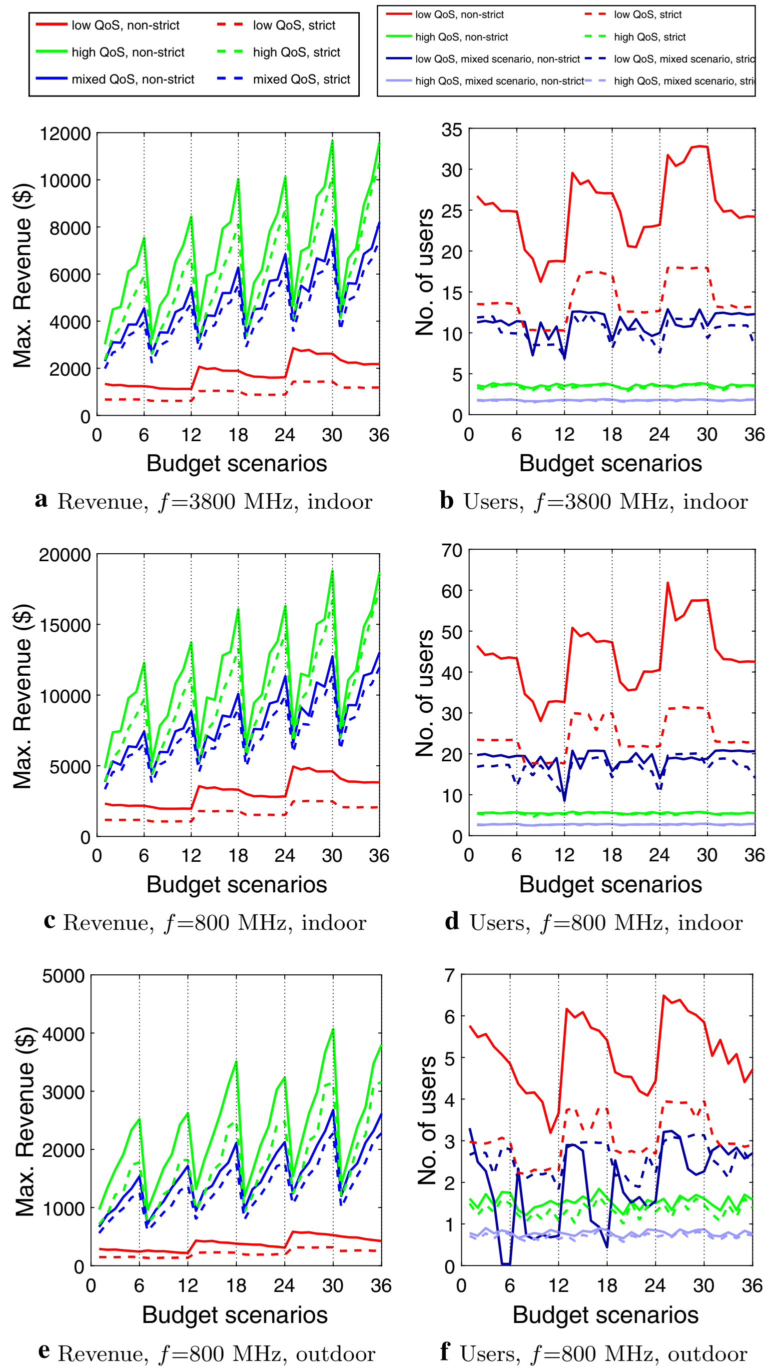

Fig. 7 Comparison of the max. revenue and the corresponding number of users for the non-strict and the strict choice of the QoS class

conclusions that we extracted from Fig. 7b still hold. First, the number of users that maximises the revenue for the low QoS scenario does not coincide with the maximum number of users (i.e., 65 users for indoor and 7 users for outdoor). Second, the number of users with Q_L for the mixed QoS scenario is in general lower for the non-strict version compared to the strict version, since the MNO has motivation to support fewer users with Q_L in order to admit more users with Q_H and charge them with high values of K. This trend becomes clearer in Fig. 7f, where the non-strict version of the mixed QoS scenario depicted as a dark blue solid line is almost always below the strict version of the mixed QoS scenario depicted as a dark blue dashed line.

6 Conclusions and outlook

The goal of this work was to unleash the potential of QoS-aware pricing for an MNO that operates within the LSA framework. The business model for the MNO was to lease spectrum to PMSE users, differentiating their prices based on whether they belong to the high or the low QoS class. We analysed three QoS scenarios: (i) all users have the same low QoS requirements, (ii) all users have the same high QoS requirements, and (iii) a mixed QoS scenario.

From the perspective of the PMSE users, we made two contributions. First, we modelled the behaviour of the users regarding how they choose between the two QoS classes, quantifying the importance that each user gives to the QoS class versus the price that it has to pay. Second, we modelled the distribution of the budget of the users for the two QoS classes. The added value of these models is that we were able to perform a fine-grained analysis, predicting the distribution of the users between the two QoS classes for each possible combination of considered prices.

From the perspective of the MNO, the first step was to analyse two case studies comparing the revenue from the three QoS scenarios. The insights were promising for the QoS-aware pricing, since for all markets that we studied, the MNO was always identifying regions of operation where it has motivation to support fewer users but charge them more, preferring either the high or the mixed QoS scenario. Then, the challenge was to choose the prices P_L and P_H so as to compute the maximum revenue that can be achieved for each QoS scenario. Our analysis revealed a consistent result that holds independent of (i) the distribution of the budgets, (ii) the way that the users choose between the QoS classes, and (iii) the values of the technical parameters. The MNO can always tune the prices so that the maximum revenue for the high QoS scenario is the highest, followed by the mixed QoS scenario and finally by the low QoS scenario. This result highlights the potential of QoS-aware pricing for the MNO. For the high and mixed QoS scenarios where QoS price differentiation can be applied, the MNO can consistently generate higher revenue than for the low QoS scenario. This is also interesting from a regulatory point of view, since the MNO has motivation to support few users charging them at a higher price instead of supporting more users at a lower price. Therefore, we identified a constant tussle in the LSA market, where the goal of the MNO (i.e., revenue maximisation) is not aligned with the goal of the market regulator (i.e., social welfare maximisation).

Through the analysis of the revenues for the different budget scenarios, we identified the impact of the budget parameters on the revenue of the QoS scenarios. The revenue for the high and mixed QoS scenarios admits local maxima when both the mean and the standard deviation of the budget distribution B_H are high (budget scenarios 6, 12, etc.). On the other hand, the revenue for the low QoS scenario admits local maxima when the mean of the budget distribution B_L and both parameters of the budget distribution B_H

are small (budget scenarios 1, 13, 25). These trends hold for any values of the technical parameters. We argue that they are useful in particular for an MNO who evaluates the business opportunities in different markets before entering into them since they provide insights for which markets have the potential to be more profitable.

Finally, we conclude with two key messages extracted from our study for the mixed QoS scenario. First, there is higher room for price differentiation for the mixed QoS scenario, since fewer users with Q_H can be admitted compared to the high QoS scenario. Second, for the non-strict version of the choice of the QoS class, the MNO usually prefers to sacrifice some of the users with Q_L in order to support more users with Q_H and charge them more. Both conclusions reinforce the message learnt, i.e., that the application of QoS-aware pricing unlocks significant revenue opportunities.

As future work, it is interesting to extend this study by introducing an additional (intermediate) QoS class and evaluate the robustness of the results. This also requires a modification for the way that the users choose among the three QoS classes. Another interesting direction is to consider an oligopoly market with two or three MNOs, analysing the churn of the users and the evolution of the revenue as the MNOs update their pricing policies. Last, but not least, our approach can be considered along with other methodologies [19] in order to assess the valuation of spectrum for other frequency bands considered also for 5G networks.

Abbreviations

BS:: Base station; LSA:: Licensed shared access; MNO:: Mobile network operator; PMSE:: Programme making and special events; QoS:: Quality-of-service.

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Authors' contributions

VGD conceived the idea, performed the theoretical analysis, generated and interpreted the results from the simulations, and wrote the paper. PM provided inputs on the initial formulation of the problem and the interpretation of the results, and was responsible for funding acquisition. Both authors read and approved the final version of the paper.

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Availability of data and materials

The datasets used or analysed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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