Power Control and Bargaining for Cellular Operator Revenue Increase under Licensed Spectrum Sharing

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Abstract Due to the constant need for ever-increasing spectrum efficiency, licensed spectrum sharing approaches, where no exclusive rights are given to any single operator, have recently attracted significant attention. Under this setting, the operators, though still selfish, have motivation to cooperate so as to provide high Quality-of-Service to their respective customers. In this context, we present an approach based on a simple charging model where many operators may coexist efficiently by combining traditional power control with bargaining, using "take it or leave it" offers. We derive conditions for a successful bargain. For the special case of two operators, we show that, through our scheme, each operator always achieves a payoff that is higher than the Nash Equilibrium payoff. We also show analytically when our scheme maximizes the social welfare, *i.e.*, the sum of payoffs. We then compare its performance through simulations with a scheme that maximizes the social welfare and a scheme that applies linear power pricing.

1 Introduction and Motivation

The number of mobile devices and the volume of mobile data traffic are growing rapidly and, consequently, new communications paradigms have arisen to meet this demand. The operators actively look for opportunities to gain more licensed spectrum; however, licensing new spectrum to cellular operators through auctions [12]

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is no longer straightforward due to the scarcity of available spectrum and the time-consuming procedure of clearing such spectrum from its legacy usage [2].

In December 2012, the Federal Communications Commission (FCC), the responsible regulatory body in the USA, published a ground-breaking proposition [1]: It identified the 3.5 GHz band that was currently used by the U.S. Navy radar operations (but characterized by light usage) as a shared-access band. In other words, the operators could jointly use this band, without having exclusive access. This idea, recently termed *licensed spectrum sharing* constitutes a complementary way to optimize spectrum usage other than the traditional approaches of either licensing spectrum or making it freely available. Licensed spectrum sharing is expected to be a key concept of 5G networks [9].

However, a great challenge to the widespread adoption of the licensed spectrum sharing paradigm is how the operators should interact with each other to satisfy their non-aligned interests [14]. In this work, we model this setup as a non-cooperative game among the wireless operators who aim at maximizing their revenues by using a simple charging scheme based on the Quality-of-Service (QoS) they offer [6].

Our contributions are the following: For the general case of N operators competing for downlink spectrum access, each one with one Base Station (BS) that transmits to one Mobile Node (MN), we propose a joint power control and bargaining scheme and discuss under which conditions it leads to operating points with higher payoffs for all operators than the traditional non-cooperating approach that leads to a Nash Equilibrium (NE). Furthermore, for the special case with 2 operators: *(i)* We show that this scheme will always lead to more preferable points than the NE for both operators. *(ii)* We prove that, through our scheme, the operating point that maximizes the social welfare (sum of payoffs) can always be reached. *(iii)* We compare its performance with a scheme based on linear pricing of the power, showing through simulations that we achieve better payoffs for most scenarios.

Note that the problem of finding a more efficient point than the NE has already been studied in the broader context of wireless networks. One direction is to consider a coalitional game [7]: Players that form the coalition act as a single entity, receive a common payoff, and then split it in a fair way using, e.g., the notion of the Shapley value. Then, the coalition is stable iff all players receive at least as much payoff as they would have received if they were on their own [7]. In our work, we do not assume coalitions among the operators, as this reflects reality more accurately.

Another direction is the application of the Nash Bargaining Solution (NBS) with a disagreement point, which is typically the NE [7]. In [13], Leshem and Zehavi compute the NBS in the context of the interference channel when there are two players and show through simulations that it significantly outpeforms the NE. In [4], the authors apply power control in the uplink using the utility function that has been proposed in [15]. They find the NBS where all players achieve equal Signal-to-Interference plus Noise Ratio (SINR) and discuss how the powers of the MNs can be driven to this operating point, which is the socially optimal solution. In our work, we assume that the operators are not willing to reveal their utility functions (*i.e.*, their powers and all their associated gains), elements that are necessary for the computation of the NBS.

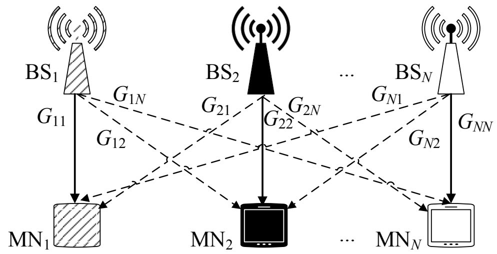


Fig. 1: Each operator i owns one Base Station, BS_i, and serves one Mobile Node, MN_i. We denote the path gain between BS_i and MN_j as G_{ij}.

Finally, pricing of the transmission power has been used as a way to find a more efficient NE. In [3], Alpcan et al. use as a utility function the throughput minus a linear function of the power. They show that, when the number of players N is lower than $L-1$, where L is the spread factor of the system, then the game admits a unique NE and their scheme converges to it. We will compare our approach with this scheme, showing that we can derive better results in terms of both payoff per operator and sum of payoffs. Moreover, another qualitative advantage of our approach is that it can be used for any spread factor $L \geq 1$.

In [8], pricing of the transmission power is used as a way to maximize the sum of payoffs. The authors show that the utility function we are using in this work belongs to a family of utility functions named Type II utilities. They then prove, by using properties of supermodular games, that their approach maximizes the social welfare when the number of players N=2. Our scheme achieves the maximum sum of payoffs as well, provided that the maximum possible power reduction is asked for in the bargaining phase. The advantage of our approach is that the required level of cooperation is lower. Indeed, with our scheme, a node i should only know the exact level of the interference that it receives from node j to decide upon the level of its offer. This information (which, for the case of 2 operators, can be easily computed by the uplink) is also needed in [8]. Moreover, in [8], each node should also know the pricing profile of the other node (*i.e.*, how much that node charges for the interference it receives) in order to update its transmission power. In the general case with N operators, with our scheme, node i still only needs to know the same information as with the case of 2 operators. On the other hand, in [8], the level of the information increases significantly: node i should know the exact level of interference experienced by all other N-1 nodes, as well as their pricing profiles.

2 System Model

We consider N operators sharing a channel of bandwidth B at a common physical area. We focus on the downlink, as the traffic in this direction is typically heavier; however, our approach can be applied to the uplink as well. As Fig. 1 shows, operator i owns one Base Station (BS), BS_i, and serves one Mobile Node (MN), MN_i.

Table 1: Game formulation.

Set of players	Set of nodes $\mathbf{N} = \{1, 2, \ldots, N\}$
Strategy of player i	$P_i \in \{P_{\min}, \ldots, P_{\max}\}$
Utility function for player i	$U_i = c_i T_i$

We consider only one MN per operator, assuming that each operator still has its own exclusive band, where it serves the rest of its MNs. Note that our approach is also directly applicable to the case of multiple BS/MN pairs per operator provided that there is network planning so that BSs of the same operator do not interfere with each other. Dealing with co-interference (*i.e.*, interference from BSs of the same operator) in the shared spectrum band is left as future work.

Each operator i controls the power P_i of BS_i and charges MN_i proportionally to the throughput that it receives. Similary to [3], the throughput of MN_i is defined as

$$T_i = B\log(1 + \mathrm{SIR}_i), \text{ where } \mathrm{SIR}_i = \frac{LG_{ii}P_i}{\sum\limits_{j \neq i}^{N} G_{ji}P_j}$$

is the Signal-to-Interference Ratio and $G_{ji} \in (0,1)$ is the path gain between BS_j and MN_i; since we assume an interference-dominated environment, we ignore the thermal noise power.

In Table 1, we model this setup as a non-cooperative game with the players being the N operators. The strategy of each player i is the transmission power P_i; the payoff that it receives is $U_i = c_i T_i$, where c_i is a positive constant. We assume that MN_i is interested in downloading files, meaning that it is willing to pay more for a better download rate. For simplicity and ease of exposition, we assume that each MN has neither a minimum nor a maximum data rate requirement.

Each player aims at maximizing its payoff. It is easy to check that this game has a unique Nash Equilibrium (NE), at which all BSs transmit at $P_{\max}$ [11].

3 Analysis

Let U_i^* be the NE payoff for player i and U_i' be its payoff at another operating point. We propose that the operators, though still selfish, decide to cooperate by applying a joint power control and bargaining scheme, in particular by using part of the revenue accumulated from the services they have offered to their associated MN in the past. In this case, one operator, say OP_1, makes a "take it or leave it" offer to another one, say OP_2, of the form: "I offer you $e_{1,2}$ units if you reduce your power by a factor of M". Defining how OP_2 is chosen is not critical, and goes beyond the scope of this work: A simple idea is that OP_1 chooses randomly OP_2. Clearly, for the bargain to be mutually beneficial, the following two conditions must hold:

$$U_1' - e_{1,2} \geq U_1^* \Leftrightarrow c_1 B \log\left(1 + L\frac{G_{11}P_{\max}}{\sum\limits_{j\neq 1,2}^{N} G_{j1}P_{\max} + G_{21}\frac{P_{\max}}{M}}\right) - e_{1,2}$$

$$\geq c_1 B \log\left(1 + L\frac{G_{11}P_{\max}}{\sum\limits_{j\neq 1}^{N} G_{j1}P_{\max}}\right). \quad (1)$$

$$U_2' + e_{1,2} \geq U_2^* \Leftrightarrow c_2 B \log\left(1 + L\frac{G_{22}\frac{P_{\max}}{M}}{\sum\limits_{j\neq 2}^{N} G_{j2}P_{\max}}\right) + e_{1,2}$$

$$\geq c_2 B \log\left(1 + L\frac{G_{22}P_{\max}}{\sum\limits_{j\neq 2}^{N} G_{j2}P_{\max}}\right). \quad (2)$$

From (1) and (2), when the corresponding equalities hold, we can compute the maximum offer, $e_{1,\max}$, that OP_1 is willing to make as well as the minimum offer, $e_{2,\min}$, that OP_2 is willing to accept.

If $e_{1,\max} \geq e_{2,\min}$, then OP_1 can find an offer that OP_2 will accept. If a successful negotiation takes place, then BS_1 transmits at $P_{\max}$ and BS_2 transmits at $\frac{P_{\max}}{M}$. In this case, each operator that does not take part in the negotiation increases its payoff as well. This is due to the fact that the throughput of their associated MN is increasing, as they receive less interference from BS_2. Otherwise, no successful bargaining can take place, and all nodes continue to transmit at $P_{\max}$, as this is the NE operating point.

An operator is interested in knowing: *(i)* Given a power reduction M, can it make a successful offer? *(ii)* If so, which is the minimum offer that it should make (clearly, this one will maximize its payoff)?

To answer these questions, note that if the operator knew all the path gains and other parameters, then it could easily compute whether it could make an offer or not and, if so, which would be the optimal offer. However, in the general case, the operator cannot "guess" whether it can make an offer or not for a requested power reduction. What it can do is to start by offering its maximum offer to the other operator. All quantities for the computation of $e_{1,\max}$ from (1) and (2) can be computed by OP_1. If the offer is rejected, then it has no motivation to make another offer for this requested power reduction, and it should choose a different operator to negotiate with. Otherwise, in next rounds of negotiations, it can reduce a bit its offer, to see if it can further improve its payoff.

4 Analysis for $N = 2$ Operators

We now investigate under which circumstances a successful bargain may arise, for the special case where there are $N = 2$ operators, denoted by OP_1 and OP_2, with a common charging parameter c_1=c_2=c. This case provides intuition about what happens in the general case. Furthermore, since in many markets there are indeed only 2 operators, it also is of practical interest.

Theorem 1 *Let $q \triangleq \frac{G_{11}}{G_{21}}$ and $r \triangleq \frac{G_{22}}{G_{12}}$ be the ratios of the path gain coefficient of the associated BS to the path gain coefficient of the interfering BS.*

1. *If $M \geq \max\{1, \frac{r}{q}\}$, then $e_{1,\max} \geq e_{2,\min}$.*
2. *If $M \geq \max\{1, \frac{q}{r}\}$, then $e_{2,\max} \geq e_{1,\min}$.*

Proof. We sketch the proof focusing on case 1 (case 2 is treated similarly). Starting from (1) and (2), the inequality $e_{1,\max} \geq e_{2,\min}$ becomes:

$$M^2 - \left(1 + \frac{r}{q}\right) M + \frac{r}{q} \geq 0 \Leftrightarrow (M-1)\left(M - \frac{r}{q}\right) \geq 0.$$

This holds for $M \geq \max\{1, \frac{r}{q}\}$.

Note that as M expresses how many times the power will be reduced, it is by definition greater than 1. Therefore, if $r \leq q$, then, for any requested reduction of the power from OP_1, there will be an interval $[e_{2,\min},\ e_{1,\max}]$ where an offer will be accepted. If $r > q$, then this interval exists for $M > \frac{r}{q}$, therefore for some power reductions an offer will never be accepted.

A direct conclusion from Theorem 1 is presented in Proposition 1.

Proposition 1 *For any requested power reduction M: if $r < q$ then OP_1 can make a successful offer; if $r > q$, then OP_2 can make a successful offer; if $r = q$, then both operators can make a successful offer.*

In other words, through this joint power control and bargaining scheme, operators can always end up at a point that is more preferable for both of them than the NE $P_{\max}$ transmission.

We now state Theorem 2 that specifies the socially optimal operating point, *i.e.*, the one that maximizes the revenue sum.

Theorem 2 *The maximum sum of revenues of the operators corresponds to one of the following operating points: A_1=(P_1, P_2)=$(P_{\max}, P_{\min})$ or A_2=(P_1, P_2)=$(P_{\min}, P_{\max})$.*

Proof. Let $V = \frac{P_1}{P_2}$. We look for the global maximum of the function

$$f(V) = cB \log(1 + qLV) + cB \log\left(1 + L\frac{r}{V}\right),$$

where $V \in \left[V_{\min} \triangleq \frac{P_{\min}}{P_{\max}}, V_{\max} \triangleq \frac{P_{\max}}{P_{\min}}\right]$ and q, r, are defined in Theorem 1. Taking the first derivative of f and setting it equal to zero, we show that:

1. When $V_{\min} < \sqrt{\frac{r}{q}} \triangleq t$, f is strictly decreasing in $[V_{\min}, t]$ and strictly increasing in $[t, V_{\max}]$. Therefore, its global maximum is either at $V_{\min}$, *i.e.*, at A_2, or at $V_{\max}$, *i.e.*, at A_1.
2. When $V_{\min} \geq t$, f is strictly increasing in $[V_{\min}, V_{\max}]$, having its global maximum at $V_{\max}$.
3. When $V_{\max} \leq t$, f is strictly decreasing in $[V_{\min}, V_{\max}]$, having its global maximum at $V_{\min}$.

We now state Theorem 3, which clarifies when our bargaining scheme can lead to the socially optimal operating point.

Theorem 3 *Let A_1 (resp. A_2) be the point that maximizes the social welfare of the system. Then, if* OP_1 *(resp.* OP_2*) applies the bargaining scheme with $M = \frac{P_{\max}}{P_{\min}}$, it will reach A_1 (resp. A_2).*

Proof. Let A_1 be the global maximum of the function f, defined in Theorem 2. By definition:

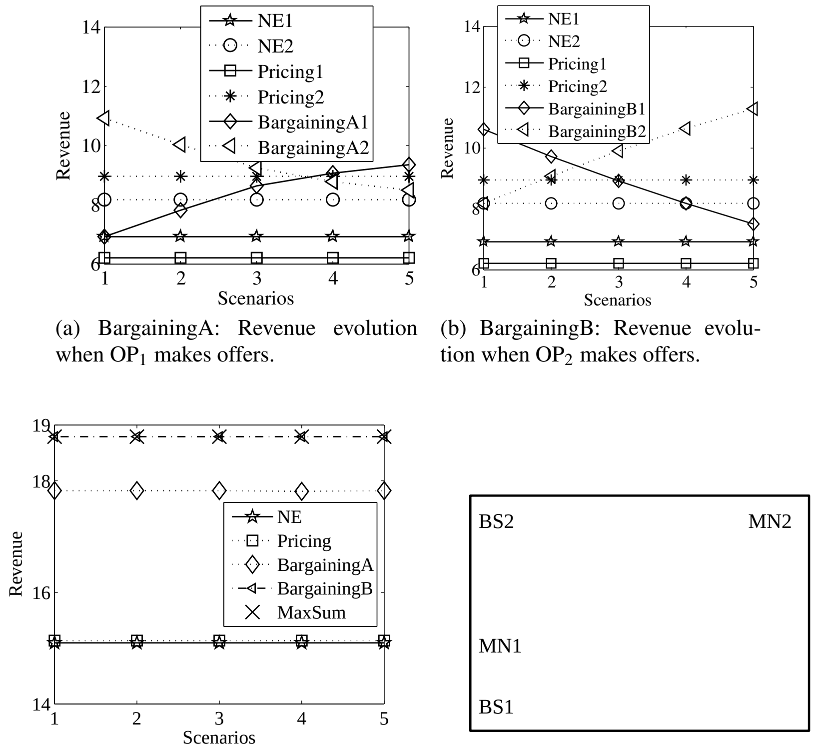
$$f(A_1) \geq f(A_2) \Leftrightarrow \log(1 + qLV_{\max}) + \log\left(1 + \frac{Lr}{V_{\max}}\right) \geq$$
$$\log\left(1 + \frac{Lq}{V_{\max}}\right) + \log(1 + LrV_{\max}).$$

After some algebra, the above inequality becomes $(q-r)V_{\max}^2 \geq q - r$, which holds if and only if $q \geq r$, since $V_{\max} > 1$. From Proposition 1, when $q \geq r$, OP_1 can make a successful offer that leads to A_1. The proof for OP_2 is omitted.

5 Performance Evaluation

We illustrate our bargaining scheme for N=2 operators. Each operator asks for the maximum possible power reduction M=32 [16]. We present two variations: BargainingA, where OP_1 makes successive offers starting from a $e_{1,\max}$ offer and progressively reducing its offer each time by 15% and BargainingB (similarly, but OP_2 makes offers). We compare them with the NE, the NE that arises after the application of pricing [3] with a linear pricing factor z (denoted as Pricing), as well as with a scheme that maximizes the sum of revenues (denoted as MaxSum) [8]. The notation Scheme$i$ refers to the payoff of OP_i with this scheme (e.g., BargainingA1); Scheme refers to the sum of payoffs.

In Fig. 2(a), we present the operating points that arise after the application of BargainingA (the parameters for this particular topology are shown in the legend). At each point, the revenues of both operators are larger than the NE revenues. At the first three points, they are larger than the Pricing scheme as well. Similar trends appear in Fig. 2(b), with BargainingB. In Fig. 2(c), we show that both schemes



(a) BargainingA: Revenue evolution when OP_1 makes offers.

(b) BargainingB: Revenue evolution when OP_2 makes offers.

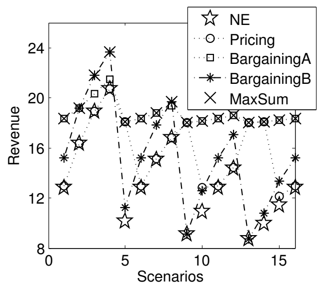
(c) Sum of revenues.

(d) Topology.

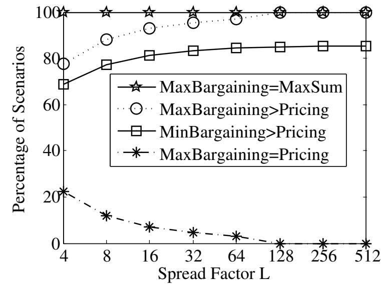
Fig. 2: Revenue under NE, Pricing, BargainingA, BargainingB, and MaxSum. G_{11}=0.5, G_{21}=0.2, G_{12}=0.05, G_{22}=0.2, L=4, B=2, c=1, z=1.5. The topology is shown in Fig. 2(d).

outperform both NE and Pricing. Actually, BargainingB also maximizes the social welfare.

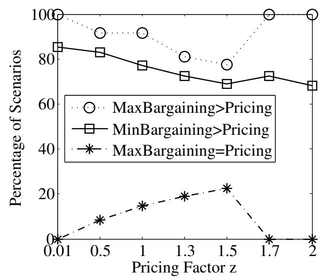
Fig. 3(a) shows the evolution of the sum of revenues for 16 scenarios. As specified by Theorem 3, in all scenarios, MaxBargaining=max{BargainingA, BargainingB} achieves the maximum sum of revenues. Moreover, in 12 scenarios, MaxBargaining strictly outperforms Pricing. In the other 4 scenarios, Pricing coincides with MaxBargaining. In Fig. 3(b), we study 124000 scenarios with the path gains G_{ij} covering a vast number of combinations. Simulations verify that in all cases MaxBargaining coincides with the MaxSum. Moreover, the sum of revenues with MaxBargaining strictly outperforms Pricing in 80% to 95% of the scenarios for small spread factors ($L \leq 64$) and 100% of scenarios for large spread factors. Furthermore, in the majority of scenarios (70% to 85%), even MinBargaining=min{BargainingA, BargainingB} strictly outperforms Pricing. Note that we depict the payoffs for Pricing for the best pricing factor z=1.5, as determined by an experimental study-see Fig. 3(c). The sum of payoffs for Pricing is lower with other z factors.



(a) G_{11}=0.2, G_{21}=0.05, G_{12} & $G_{22} \in \{0.05, 0.2, 0.5, 0.95\}$, L=4, z=1.5.



(b) Sum of revenues as a function of L. $G_{ij} \in \{0.01, 0.06, 0.11, \ldots, 0.96\}$, z=1.5.



(c) Sum of revenues as a function of z. $G_{ij} \in \{0.01, 0.06, 0.11, \ldots, 0.96\}$, L=4.

Fig. 3: Sum of revenues under NE, Pricing, BargainingA, BargainingB, and MaxSum. B=2, c=1.

6 Conclusions

The goal of this work was to study the emerging concept of licensed spectrum sharing, where no exclusive rights are given to any single operator, under the prism of game theory. Assuming that the operators charge their customers based on the throughput that they offer to them, we define a non-cooperative game that has a unique Nash Equilibrium, where all operators transmit at $P_{\max}$. Our work starts with the observation that the operators, though still selfish, have motivation to cooperate to end up at more efficient operating points that increase their revenues. We develop an incentives-based mechanism that enables this cooperation, by combining traditional power control with bargaining, using "take it or leave it" offers. Then, we show that, even in the general case, where N operators share the same portion of the licensed spectrum, there are conditions that guarantee that a more efficient operating point may arise. We then deepen our results for the special case of two operators. *(i)* We show that for any level of requested power reduction, at least one of the two operators can make an offer than can be accepted and leads to a more efficient operating point than the NE. *(ii)* We derive a set of bargaining strategies that lead to the operating point that maximizes the social welfare of the system, demanding less exchange of messages than the state-of-the art. *(iii)* We show that our scheme outperforms the standard idea of linear pricing of the transmission power as a way of finding more efficient operating points in terms of both revenues per operator and sum of revenues.

Our conclusions are aligned with previous works (e.g., see [10]) that argue that spectrum sharing among the wireless operators has the potential to improve significantly the network efficiency. Concerning the future directions, it would be interesting to compare our scheme with the outcome of a spectrum sharing game where the operators do not play simultaneously, but hierarchically [5]. Moreover, a natural extension would be to simulate scenarios with $N > 2$ operators that apply our bargaining mechanism; we could evaluate our mechanism in terms of social welfare, examining whether a theorem similar to Theorem 3 can be proved for N operators. Finally, it is interesting to examine the more realistic case where a customer has made an agreement with his operator that he will not be charged when his throughput is lower than some minimum value.

7 Acknowledgment

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