Abstract—This paper proposes a two-layer Joint Radio Resource Management (JRRM) framework to improve the efficiency in multi-radio and multi-operator cellular scenarios. On the one hand, the intra-operator JRRM relies on fuzzy-neural mechanisms with economic-driven reinforcement learning techniques to exploit radio resources within a single operator domain. On the other hand, inter-operator JRRM allows subscribers to get service through other operators in case the home operator network is blocked. Simulation results in a number of different scenarios show that inter-operator agreements established in a cooperative scenario bring benefits to both operators and users, enabling an efficient load management and increasing the operators’ revenue.

Keywords—Heterogeneous wireless networks; fuzzy neural; B3G systems; multi-operator; reinforcement learning.

I. INTRODUCTION

The perspective of Beyond 3G (B3G) mobile communications systems is that of heterogeneous networks, where the multiplicity of access technologies will constitute an access interface to a common IP-based (Internet Protocol) core network. Wireless networks differ from each other by air interface technology, cell-size, services, price, access, coverage and ownership. For this purpose, internetworking architectural issues concerning heterogeneous networks have been widely covered in the literature [1]-[6]. In addition to the need for a proper interworking among Radio Access Technologies (RATs), a new dimension is introduced into the Radio Resource Management (RRM) problem. That is, instead of performing the management of the radio resources independently for each RAT, some form of overall management of the pool of radio resources can be envisaged. Joint Radio Resource Management (JRRM) is the foreseen process to manage dynamically and coordinate the allocation and de-allocation of radio resources among different radio access systems, so that a more efficient usage of the radio resources will follow. By means of JRRM, a user can, at any time and anywhere, choose the RAT that best suits its needs in terms of application, perceived quality, cost, thus aiming at being Always Best Connect (ABC) [7], taking full advantage of terminals with reconfigurable capabilities [8].

In such a complex scenario, to make only technical considerations about the dynamic behavior of the network is not enough. For example, it should be considered that both users’ and network operators’ satisfaction (i.e. operator revenue) strongly depend on resource allocation and also on pricing policies. As a result, in this paper micro-economic concepts, which have already been applied to RRM related issues such as admission control [9], power control [10] and packet scheduling [11], have been introduced together with radio-interface management decisions.

In a previous work of the authors [12], it was proposed a fuzzy neural based strategy for JRRM operation in a single operator scenario, including a reinforcement learning mechanism to adapt the algorithm in order to achieve the desired QoS constraints. Later on, in [13], an economic-driven fuzzy neural based JRRM was proposed, expanding the concepts in [12]. The resulting framework introduces techno-economic cognitive mechanisms, so that the JRRM decisions adapt themselves to the changing traffic, mobility and propagation conditions, in order to keep the target users’ satisfaction.

This work extends the previous works to a multi-operator scenario. In fact, the network deployment for a given operator is usually designed to support the expected traffic level at the busy hour. Nevertheless, the actual offered traffic may differ from the planned level, since the inherent dynamic nature of the mobile cellular scenario makes the offered traffic profiles difficult to be accurately predicted along time and space. These mismatchings could be experienced due to e.g. random call/session generation processes in the short term or faster/slower service penetration than predicted in the long term. In that case, the network operator faces a waste of radio resources if the actual traffic is below the planned level or non-satisfactory QoS if the traffic is higher than expected. In both cases, inter-operator radio resource trading may be a good solution towards a more efficient overall radio resource usage, thanks to the complementarities existing among the different operators in terms of traffic demand and infrastructure available.

In the literature, JRRM in a multi-operator context has been faced from different perspectives. In [14] resource brokerage functionalities in a B3G network, enabling cooperation among different network providers, are introduced. On the other hand, [15] considers the network operators as competitive actors in a scenario characterized by a user centric vision. Finally, in [16]...
new types of actors which can be introduced in a multi-RAT and multi-operator scenario are discussed.

In this framework, this paper proposes a novel two-layer JRRM strategy to fully exploit the available radio resources and to improve the network operators’ revenue. In particular, the first layer of the proposed JRRM approach aims at managing the radio resources associated with a single operator (i.e. intra-operator JRRM); successively, if the current traffic conditions cannot be targeted by the intra-operator JRRM, the second layer of the proposed approach is triggered in order to trade radio resources with other operators (i.e. inter-operator JRRM). The intra-operator approach takes as a basis the scheme already presented by the authors in [12][13]. In turn, the inter-operator JRRM strategy is built upon extending intra-operator mechanisms by means of a multiple objective decision making process based on the combination of fuzzy set theory and the Analytic Hierarchy Process (AHP) [17][18].

It is worth mentioning that this proposal is based on the idea that both the operators participating in the trading process are benefited by the establishment of inter-operator agreements. In particular, the operator “renting” radio resources takes advantage of this exchange in the short term, in terms of revenue coming from the service provision for the user. On the other hand, the operator “borrowing” radio resources is benefited in the long term since the user, instead of being blocked, is provided with service in a transparent manner and consequently is not motivated to churn.

The rest of the paper is organized as follows. In Section II some micro-economic concepts are introduced and applied to an intra-operator economic-driven JRRM. In section III, the inter-operator JRRM mechanism and the role of the so-called metaoperator are introduced. Section IV is devoted to describe the simulation scenario where the proposed framework is evaluated. Section V discusses some representative results. Finally, Section VI summarizes the conclusions.

II. INTRA-OPERATOR ECONOMIC-DRIVEN JRRM

A successful realisation of the cellular wireless business needs to find a good balance between economics and RRM, since pricing and resource deployment and allocation strategies determine both the user’s satisfaction and the operator’s exploitation results. Users without adequate QoS are likely dissatisfied. Additionally, users’ feelings also depend on the price paid for the service, since users perceiving good QoS but at a very high price may also be dissatisfied. In the following, two metrics are identified in order to quantify the user and the network operator satisfaction, respectively.

A. User-centric metric: user acceptance

The notion of user acceptance can be defined as the probability that the users are satisfied with the service provided by the network in accordance to the price they are paying. It is claimed to be an appropriate indicator of the user satisfaction, since it captures the trade-off between the price paid and the perceived quality. Specifically, the acceptance \( A(u, p) \) is an increasing function of the utility \( u \) that the user perceives and a decreasing function of the price \( p \) [19]:

\[
A(u, p) = 1 - \exp(-Cu^\mu p^{-\epsilon})
\]

where \( C, \mu \) and \( \epsilon \) are constants representing the different user sensitivity to utility and price.

In turn, the utility is a function that depends on the specific service characteristics and the elasticity of the applications. Inelastic applications (e.g. real time voice) are characterized by a step utility function depending on e.g. whether the allocated bandwidth \( B \) is above or below a given threshold. On the other hand, elastic applications (e.g. data applications) exhibit a smoother function of the allocated bandwidth. Particularly, the utility is defined in this paper as [19]:

\[
u(B) = \frac{(B/K)^\xi}{1+(B/K)^\xi}
\]

where \( 0.2 \leq K \leq 4.2 \) and \( 2 \leq \xi \leq 20 \) are tunable parameters.

B. Network-centric metric: revenue

From the network operator point of view, the revenue is considered as the network metric to define the operator satisfaction. The operator revenue can be formulated as a function of the price the users are paying and the user acceptance, in the sense that only users accepting the service will be in practice generating revenue. This leads to the following definition of revenue [19]:

\[
R = \sum_{i=1}^{N} p_i A(u_i(B_i), p_i)
\]

where \( N \) is the number of users, \( p_i \) is the price paid by the \( i \)-th user, \( B_i \) its bandwidth and \( A(u, p) \) the user acceptance.

In order to analyze and compare profitability between operators, a modification of the \( R \) indicator will be used in this paper, and will be referred to hereafter as profit. It is calculated by subtracting the expenses faced by the operator from its revenue. The expenses that will be considered only include the cost of infrastructure deployment.

Taking advantage of the micro-economic concepts just introduced, the proposed economic-driven JRRM is based on fuzzy neural methodology [12] and its objective is to provide, for each user, the most appropriate RAT and bit rate allocation \( B \), taking into account the following inputs:

a) Technical inputs: They consist of measurements of the signal strength \( SS \) and resource availability \( RA \) for each RAT \( k \). Mobile speed \( MS \) is included to take into consideration mobility constraints in the RAT allocation.

b) Economic inputs: They consist of the price \( p_j \) to be paid for service \( j \) and the target total user acceptance \( A^* \).

c) Operator policies: They consist of a set of high-level directives that specify the construction of the inference rules in the fuzzy neural block.

In particular, the RAT is selected making use of the fuzzy neural algorithm’s outputs referred to as FSDs (Fuzzy Selected Decision), which take values in the range \([0,1]\). The i-th FSD value indicates the appropriateness of selecting the i-th RAT in front of the others.

The proposed economic-driven JRRM algorithm is depicted in Figure 1 and consists of a Fuzzy Logic Controller (FLC) together with a reinforcement learning algorithm. The FLC module is based on three procedures denoted as
fuzzification, inference engine, and defuzzification (the interested reader is referred to [12] for details on the fuzzy neural JRRM basics). The reinforcement learning procedure provides the system with adaptive capabilities embedding cognitive-based mechanisms that let the network be aware of its current status.

In order to include the economic-driven aspects into JRRM decisions, the reinforcement signal considered here is the overall user acceptance $A(u,p)$. The objective of the learning algorithm is to minimize a certain error function defined as the difference between the current average user acceptance over time $A(t)$, and a certain target value $A^*$. Then, as a result of the error minimization, the reinforcement learning algorithm is able to maintain the average user acceptance to the target value $A^*$, thus guaranteeing a certain level of user satisfaction in the network. The details about the reinforcement learning procedure are given in [12], where only technical drivers were considered (i.e. only RAT and bit rate considerations).

III. INTER-OPERATOR JRRM

In order to further improve the radio resource usage achieved by means of intra-operator JRRM, this paper proposes to exploit the potential complementary characteristics of traffic distribution experienced by $N$ operators, through radio resource trading among them.

In particular, the envisaged technical solution assumes a previous establishment of inter-operator agreements maintained and guaranteed by a Metaoperator, (see Figure 2), to which each network operator can transfer its rights in case the intra-operator JRRM cannot meet the user satisfaction constraints. In this way, the potentially dissatisfied user can be given access to the service through another network operator, selected as a result of a decision making process performed by the Metaoperator, who acts as a third trusty party. In the following we will refer to the operator the user has a contract with as the $H$-operator (i.e. Home operator), and to the operator who is actually providing the service to the user as the $S$-operator (i.e. Serving operator). From Figure 2 it can be noticed that the $i$-th network operator is characterized by its own intra-operator JRRM entity, which makes decisions regarding the RAT and the bandwidth, within its own network domain.

When the $i$-th JRRM makes a decision leading to a blocking/dropping, the $i$-th network operator sends to the Metaoperator a request of admission for the potentially blocked/dropped user to another network operator, informing about the contracted QoS. The trading agent asks the rest of $N-1$ operators willing to accept the user, to trigger their JRRM entity and to return the information corresponding to the potential allocation of the user. According to the information collected from the $N-1$ potential serving operators, a decision process is triggered at the Metaoperator and the most suitable S-operator is selected.

Figure 1 Economic-driven JRRM

A. Trading agent

The trading agent implemented in the Metaoperator is the actor that provides the bridge among different operators by making transactions for offering and demanding radio resources. Different forms of market basis can be envisaged (e.g. auction mechanisms, game theory etc.). In particular, in this paper the trading agent is implemented by means of a multiple criteria decision maker based on the combination of fuzzy set theory and AHP [17][18]. In fact, in a multi-RAT and multi-operator scenario the choice of the most suitable RAT and bandwidth to allocate depends on many heterogeneous inputs (i.e. technical, subjective, economic, etc), so that a framework capable of taking into account multiple criteria to make a decision is considered as an appropriate choice.

In a scenario where $N$ operators (OPs) are coexisting, the multiple objective decision maker aims at selecting the most appropriate S-operator among the $N-1$ alternatives, taking into account a certain number of decision criteria. In particular, in this paper the following criteria $C_1$ and $C_2$ are considered:

- $C_1$ - FSD
- $C_2$ - User acceptance, $A$

The FSD value is considered as an appropriate decision criterion since its computation captures the main techno-economic indicators reflecting the specific network context, as explained in Section II. In turn, the user acceptance of the service has been selected as the second considered criterion because it encompasses both utility and pricing considerations, thus being a reliable indicator of both the user satisfaction and the operator revenue.

In particular, whenever a certain user is to be transferred to another operator, the two decision criteria with respect to the $i$-th alternative operator OP$_i$ are $C_{i1}=$FSD, and $C_{i2}=$A$_i$ which are, respectively, the FSD associated with the RAT that would be
selected for the user by OP, if it was chosen as S-operator, and the corresponding user acceptance.

According to the theory of decision based on fuzzy sets [18], the decisions are made in two steps:

1. Select for each alternative OP, its smallest value for any of the criteria. So, for OP, the decision value is \( D_i = \min(FSD_i, A) \)

2. Select as optimal decision the operator with the highest value \( D_i \).

The procedure presented so far assumes that the two decision criteria are equally important. However, if the decision criteria had different degrees of importance, it would be possible to combine the decision process described above with a procedure referred to as AHP, which is a very powerful technique that allows making decisions taking into account multiple weighted criteria depending on their relative importance to the problem [17][18].

### B. Pricing

The transaction between H-operator, Metaoperator and S-operator has to be transparent to the user involved in the trading process. Consequently, the price actually charged to the user should be independent of the operator it is actually associated to different operators depending on the specific case study. Deployment #1 (see Figure 3 (a)) consists of 4 UMTS base stations, 2 GERAN base stations and one WLAN access point. Cell radii are 150m for WLAN, 650m for UMTS and 1km for GERAN. Deployment #2 consists of 2 UMTS base stations, 2 GERAN base stations and one WLAN access point (see Figure 3 (b)). Table 1 summarizes the deployment characteristics including the cost per frequency carrier computed over a unit of time [22].

**Table 1 Infrastructure deployment**

<table>
<thead>
<tr>
<th>Station</th>
<th>Base</th>
<th>No Freq</th>
<th>Cost Freq</th>
<th>No Freq</th>
<th>Cost Freq</th>
</tr>
</thead>
<tbody>
<tr>
<td>WLAN</td>
<td>1</td>
<td>0.0112</td>
<td>1</td>
<td>0.0112</td>
<td></td>
</tr>
<tr>
<td>UMTS1</td>
<td>1</td>
<td>0.0865</td>
<td></td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>UMTS2</td>
<td>1</td>
<td>0.0865</td>
<td>1</td>
<td>0.0865</td>
<td></td>
</tr>
<tr>
<td>UMTS3</td>
<td>1</td>
<td>0.0865</td>
<td>1</td>
<td>0.0865</td>
<td></td>
</tr>
<tr>
<td>UMTS4</td>
<td>1</td>
<td>0.0865</td>
<td></td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>GERAN1</td>
<td>4</td>
<td>0.018*4</td>
<td>1</td>
<td>0.018</td>
<td></td>
</tr>
<tr>
<td>GERAN2</td>
<td>4</td>
<td>0.018*4</td>
<td></td>
<td>1</td>
<td>0.018</td>
</tr>
</tbody>
</table>

A mobility model with users moving according to a random walk inside the coverage area is adopted with a randomly assigned mobile speed in the interval [0,50] km/h and a randomly chosen direction. The propagation model considered for UMTS and GERAN is given by \( L(dB)=128.1+37.6 \log d \) (km) [20]. For WLAN the propagation losses inside the hotspot are modeled by \( L(dB)=20 \log d(m)+40 \) [21]. The beginning and the end of the user’s activity periods are defined according to a Poisson scheme with an average of 6 calls per hour and user and average call duration of 180 seconds. The set of available bit rates in UMTS are \{32 kb/s, 48 kb/s, 64 kb/s, 80 kb/s, 96 kb/s, 112 kb/s, 128 kb/s, 192 kb/s, 256 kb/s, 320 kb/s, 384 kb/s\}, considering a single UTRAN FDD carrier with maximum allowed uplink load factor 0.75. For GERAN, the set of bit rates is \{32 kb/s, 48 kb/s, 64 kb/s, 80 kb/s, 96 kb/s\}, assuming a total of four carriers available and coding scheme CS-4. For WLAN it is considered that the total bandwidth available (11 Mb/s) is equally distributed among the WLAN users (i.e. the higher the number of users the lower the bandwidth per user will be). It is also assumed that no more WLAN users are accepted when the bandwidth per user is less or equal than 384 kb/s.

The retained performance metrics are the blocking (a user is blocked if at the session start the JRRM algorithm assigns a bit rate of 0 kb/s) and dropping (a user is dropped whenever,
after a change in the serving cell, the JRRM assigns a bit rate of 0 kb/s) probabilities.

Simulation results have been obtained considering that the target user acceptance probability is retained to $A^* = 0.8$, which is considered a reasonable choice since it means that during 80% of the time the user is satisfied with the service perception and the price paid for it.

In order to evaluate the proposed framework, we consider simulation scenarios where two operators, referred to as OP1 and OP2, are coexisting. Different simulation scenarios can be analyzed depending on the infrastructure deployment and the market share of each operator. Concerning infrastructure deployment, the investments of the two operators can be either the same (i.e. symmetric infrastructure deployment) or different (i.e. asymmetric infrastructure deployment). In the symmetric deployment both OP1 and OP2 are characterized by the infrastructure deployment #1 (notice that this corresponds to an investment of 0.5 economic units). In the asymmetric deployment, OP1 is characterized by the infrastructure deployment #1 (i.e. 0.5 economic units investment) whereas OP2 is characterized by the infrastructure deployment #2 (i.e. investment is reduced to 0.22 economic units). In terms of market share, the operators can be characterized by either the same (i.e. balanced market share) or a different (i.e. unbalanced market share) number of subscribers. As a result, this paper studies four simulation scenarios, as summarized in Table 2.

Table 2 Simulation scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Infrastructure Deployment</th>
<th>Market share</th>
</tr>
</thead>
<tbody>
<tr>
<td>A)</td>
<td>Symmetric</td>
<td>Balanced</td>
</tr>
<tr>
<td>B)</td>
<td>Symmetric</td>
<td>Unbalanced</td>
</tr>
<tr>
<td>C)</td>
<td>Asymmetric</td>
<td>Balanced</td>
</tr>
<tr>
<td>D)</td>
<td>Asymmetric</td>
<td>Unbalanced</td>
</tr>
</tbody>
</table>

In addition to this, three different business models are considered:

A. No Inter-Operator Agreements (NIOA)

This business model considers the classical approach in which the operators coexisting in the scenario are not cooperating in order to take advantage of the complementary characteristics of their temporal/spatial traffic distribution.

B. S-Operator Gets All Revenue (SOGAR)

Inter-operator agreements have been established with $\alpha=1$, so that the S-operator receives 100% of the income deriving from supporting the service requested by the user of another operator.

C. Shared Revenue Based on Load (SRBL)

Inter-operator agreements have been established and $\alpha=\eta$, where $\eta \leq 1$ is the normalized load. Then, the S-operator receives a percentage of the income from its subscribers, which depends on the average load of the S-operator, so that the more loaded the S-operator, the higher the income that has to be guaranteed to it.

Finally, for further details about the parameter definition of the fuzzy neural network the reader is referred to [12].

V DISCUSSION AND RESULTS

Simulation results obtained in the scenarios summarized in Table 2 are presented and discussed in this section. The number of users in all presented figures represents the sum of users belonging to OP1 and OP2.

A. Scenario A

This scenario considers symmetric conditions for the two operators in terms of both infrastructure deployment and market share. In this sense, the operators are likely to be highly loaded in the same time and space conditions, thus reducing to the minimum their complementary characteristics that can be exploited by the proposed inter-operator JRRM mechanisms. Then, in such a situation, the cooperation among operators occurs mainly to face blockings or droppings associated with sporadic overload situations. Figure 4 compares the performances in terms of blocking and dropping probabilities obtained in the considered simulation scenario for two cases: inter-operator agreements have been established with SOGAR business model and inter-operator agreements have not been established (NIOA).

Simulation results show an important reduction in both blocking and dropping probabilities when inter-operator agreements have been established. The benefits obtained in case of inter-operator agreements can also be read in terms of increment of radio interface usage. In fact, if the maximum tolerable blocking probability is set to e.g. $P_B = 2\%$, the maximum number of admitted users increases up to 36% (i.e. capacity gain $\Delta C$ from 250 to 340 users), as it is shown in Figure 4, with respect to the case that inter-operator agreements have not been established. This capacity gain can be translated into an operator profit gain $\Delta P$ of up to 34%, as it is shown in Figure 5.

![Figure 4 Blocking and Dropping probability performance comparison – scenario A with two operators](image)

![Figure 5 Operator Profit comparison – scenario A](image)
Notice as well that, since the infrastructure deployment is symmetric and the market is equally shared between the two operators, the profit is almost equally distributed between the two operators, so that for sake of simplicity, Figure 5 just represents the aggregated operator profit for the two operators. In addition, the choice of the business model (i.e. SOGAR and SRBL) does impact neither the profit distribution between the operators, nor their performance figures, since the percentage of exchanges between OP1 and OP2 is the same in the two directions.

Finally, it is worth mentioning that when more than two operators are involved in the trading process the radio resource usage can be even improved. For example, when three operators are coexisting in a scenario A, the increment of capacity, with respect to the case that inter-operator agreements have not been established, increases up to 54% (i.e. capacity gain from 350 to 540 users), as it is shown in Figure 6, which can be translated into a revenue gain up to 60%. The reason is that more operators are taking part in the trading process, thus improving the complementary characteristics of the traffic in the scenario.

Figure 6 Blocking and Dropping performance comparison – scenario A with three operators

B. Scenario B

In this scenario, the market is not equally shared between the operators, and in particular OP1 controls 2/3 of the market share, whereas the remaining part is managed by OP2 (i.e. with 300 users, 200 users are OP1 subscribers, so that OP1 is their H-operator, whereas the remaining 100 are OP2 subscribers, so that OP2 is their S-operator).

Simulation results show that the probability of OP2 acting as S-operator for OP1’s subscribers is much higher than the reverse, since OP1 has more subscribers than OP2 and the infrastructure deployments of the two operators are the same. In particular, with a low load of 200 users, 100% of the inter-operator exchanges are in OP1→OP2 direction. However, when the number of users increases, some blockings or droppings start to occur also with OP2 and therefore some users need to be transferred in OP2→OP1 direction. As an example, with 400 users in the scenario, 85% of exchanges are OP1→OP2, and the remaining 15% are OP2→OP1.

Other considerations can be made observing Figure 7, which shows the OP1 and OP2 profits, respectively, for different business models.

First of all, it is worth mentioning that in this scenario OP2 is the operator that is more benefited in economic terms by the establishment of agreements with OP1. In fact, the direction of exchanges is mostly in the OP2 direction. However, also OP1 takes advantage of the agreements since some users that would have been blocked have instead been satisfactorily served by OP2. The exchange operation is transparent to the users, so that in the long term they are not motivated to churn from OP1 to another operator

In addition to this, the operator with the highest number of subscribers (i.e. OP1) is benefited in terms of profit by the business model SRBL, which guarantees to the H-operator a percentage of revenue deriving by its subscribed users. On the other hand, the operator characterized by the lowest portion of market share (i.e. OP2), is more benefited in terms of profit by the business model SOGAR, which guarantees to the S-operator the 100% of the revenue derived by inter-operator exchanges.

Finally it is worth noting that, the maximum number of admitted users for $P_{th}=2\%$ is increased up to 54% (i.e. capacity gain from 220 to 340 users), which can be translated into a profit gain up to 43%, with respect to the case that inter-operator agreements have not been established, when considering the aggregated profits of the two operators. The reason for this further percentage improvement in operator profit in scenario B compared to scenario A, is that in scenario A the two operators are on average equally loaded (i.e. balanced market share), which means that the complementary characteristics to be exploited by the trading mechanisms among operators are reduced to the minimum. On the contrary, the unbalanced market share increases the complementary characteristics of traffic distribution to be exploited by the proposed algorithm.

Figure 7 OP1 and OP2 Profits for different business models – scenario B

C. Scenario C

In this scenario, two operators characterized by different infrastructure deployments and the same market share are considered.

Observing the operator profit simulation results depicted in Figure 8, two tendencies can be highlighted depending on whether the considered traffic demand is low (i.e. 60 or 80 users) or high (i.e. more than 80 users).

For business model NIOA, when the traffic demand is low, the OP1 and OP2 profits are almost similar, despite the different infrastructure deployments. The reason is twofold. On the one hand, the revenue of OP1 is not high enough to compensate for the high infrastructure investment. On the other hand, due to the infrastructure deployment of OP2, which provides only GERAN coverage in an area of the scenario (see Figure 3 (b)), more blockings/droppings are likely to occur also
In case of low traffic demand, thus reducing the OP2’s revenue and consequently OP2’s profit.

In addition to this, when the revenue distribution is regulated by the business model SRBL, which guarantees a percentage of revenue to the H-operator (notice that the direction of exchanges in scenario C is in most of the cases OP2→OP1), the lower cost of infrastructure invested by OP2 and the percentage of revenue \((1-\alpha)p\) coming from his subscribers that have been served by OP1, let OP2 achieve a higher profit than OP1 (e.g. with 60 users, the profit of OP2 is 59% higher than the profit of OP1).

In turn, in case of SOGAR business model, since the direction of exchanges is mostly OP2→OP1, the additional revenue \(\alpha p\) coming from OP1 subscribers lets OP1 achieve a higher profit than OP2.

On the other hand, with more than 80 users, regardless the considered business model, OP1 outperforms OP2 in terms of profit, since it is capable of providing service to more users than OP2, which in turn has to use the OP1 infrastructure in order to provide service to them. So, when the traffic demand is high, the higher operator revenue that can be achieved by serving a higher number of users and by resource trading, allows OP1 to compensate for the high cost of the infrastructure investment and to make higher profit than the operator that had invested less in infrastructure.

It is worth noting that SOGAR model guarantees that the operator investing more in infrastructure is benefited to a larger extent in terms of profit by the cooperative establishment of inter-operator agreements. In particular, with 120 users, the profit of OP1 is 1.3 and 2.6 times higher than the profit of OP2, with SRBL and SOGAR models, respectively. Besides, it is worth mentioning that the cost of infrastructure of OP1 is 2.3 times higher than the one of OP2 (i.e. the cost of infrastructure of OP1 and OP2 is 0.5 and 0.22, respectively), which is the same order of magnitude of the profit ratio in case of SOGAR (i.e. 2.6).

In this sense, we conclude that SOGAR business model guarantees a fairer distribution of income among the cooperative operators than SRBL business model, by guaranteeing a higher revenue to the operator that actually provides service to the users. In this model, the H-operator benefits in a more indirect way, as long as its subscribers do not face service limitations and, consequently, do not feel motivated to churn.

D. Scenario D

In this scenario it is considered that OP1 invested almost twice in network infrastructure (i.e. deployment #1) compared to OP2 (i.e. deployment #2). With respect to the market share, it is considered that OP1 has also twice subscribers than OP2.

Simulation results obtained in this scenario lead to similar conclusions with respect to those already described for the other scenarios, so that, due to space constraints, they will not be shown. In particular, they reflect an increase in profit when inter-operator agreements are established, thus exploiting the capacity gain. In addition, due to the spatial distribution of the infrastructure deployment, which provides only GERAN coverage in an area of OP2’s scenario (see Figure 3 (b)), the direction of exchanges is mostly OP2→OP1. So, OP2 is not economically benefited in the short term by the business model SOGAR, but its benefit consists of providing service for its subscribers despite the lack of available radio resources. For instance, it is worth mentioning that in case of inter-operator agreements the OP2 blocking probability \(P_b\) never exceeds 2%, for all the cases studied. On the other hand, for SRBL, the profit of both OP1 and OP2 takes advantage of the inter-operator agreements, but the improvement of the OP1 profit is lower than in the SOGAR case, since a percentage of revenue is guaranteed to the H-operator.

VI CONCLUSION

In this paper, a two layered approach to improve radio resource usage and operator’s revenue has been presented by establishing inter-operator agreements that exploit the complementary characteristics of traffic distribution and infrastructure deployment in the different operators’ domains. These agreements are maintained by means of a Metaoperator implemented through fuzzy sets theory and AHP.

The approach has been evaluated in four scenarios where two operators are coexisting, each one characterized by a certain infrastructure deployment and a certain market share. The profit has been introduced as a reliable indicator of the financial situation of the operator since it includes in its computation the revenue coming from the service provision to the users and the operator’s investment in infrastructure.

In addition, three different business models have been evaluated depending on how the revenue generated by the users transferred from one operator to another is shared between the involved parties.

Simulation results have shown that the establishment of inter-operator agreements brings benefits in terms of both network performances (i.e. blocking/dropping probability and capacity gain) and operators’ revenue. These benefits can be even improved if the two operators are characterized by complementary traffic distribution, e.g. unbalanced market share, or if more than two operators take part in the trading process.

Furthermore, the business model guaranteeing the 100% of revenue derived by a user to the operator that actually provides service for it (i.e. the S-operator) benefits the operator that correctly estimates the infrastructure deployment that will be needed to satisfy the service demand, and properly invests in it.
In this case, the operator the user has subscribed a contract with (i.e. H-operator) takes advantage of the fact that its users, having been provided with service in a transparent manner, are not motivated to churn.

Finally, the business model guaranteeing a percentage of revenue to the H-operator, benefits the S-operator in a lower percentage with respect to the previous case.

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