

# Optimum Selection of Access Networks within Heterogeneous Wireless Environments Based on Linear Programming Techniques

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**Abstract.** In this work we analyze the possibilities which are brought about by the use of linear programming techniques in the framework of access selection procedures within heterogeneous wireless network environments. We present a tool which has been designed and implemented (based on the *GLPK* package) to tackle this problem. This tool, starting from a particular network model, can be used to retrieve the optimum assignment of access elements. To fulfil this goal, we introduce a flexible cost (*utility*) function, which allows modulating the relevance given to the different aspects which could be taken into consideration while deciding the access alternative to be used: connection with a preferred operator, minimizing the number of handovers, or link quality, amongst others. Afterwards, the tool is used to study a set of canonical access selection strategies, so as to establish the combination of parameters which might lead to better performances.

## 1 Introduction

The recent proliferation of different wireless communication technologies has brought about the need of developing proper mechanisms to handle heterogeneity at the devices worn by regular users. The consequence is that near-future communication scenarios (in some cases they are referred to as 4G) will be characterized by offering a broad range of access alternatives, not only considering the involved technologies, but also from the point of view of the entities which manage the available networks.

In the aforementioned framework, it becomes necessary to revisit the new challenges which pop up in the access selection procedures, which are nowadays mostly based on non-automated processes, requiring in several cases, the direct intervention of the end-user. In contrast with this legacy approach, novel automated algorithms to ensure the most appropriate access alternative to the end user are deemed necessary; these should take into account various aspects, such as the user preferences, the particular network condition, as well as the punctual requirements of the current services.

In order to reach such an optimum performance, the involved network entities (base stations, access points, users, operators, etc.) must cooperate between

them, by means of novel signalling mechanisms to transport the required control information. This information would, obviously, have a local *scope*, limited to the end-user, since he might not be aware of the potential consequences his decision can have over other network nodes. Additionally, in order to establish the suitability of the employed access mechanisms, it is fundamental to be aware of which is actually the best performance to be reached.

In this work we aim at analyzing such optimum behavior, using linear programming techniques. In this sense, we model a heterogeneous wireless networking scenario (embracing various technologies and operators) as an optimization problem, using an objective, *utility*, function, able to modulate the weight given to the various merit parameters. The *GLPK* library is used to solve the corresponding problem. The achieved results might help to establish, amongst others, the combination of the various weights which should be used by the access selection algorithms so as to guarantee an optimum behavior.

In order to fulfil the previously established goal, this paper has been structured as follows: Section 2 discusses some of the related work, highlighting the main differences with our approach. Section 3 presents the optimization problem to be solved with the framework depicted in Section 4. Section 5 describes the networking scenario which will be used to analyze a number of access selection strategies, whose performance will be discussed in Section 6. Finally, Section 7 concludes the paper, advocating some items which are left for future work.

## 2 Related Work

As it has been previously mentioned, the broad range of currently available radio access technologies (RAT), together with the increase of the number of devices which actually integrates various of them are some of the elements which promote the path towards future wireless access systems, mainly characterized by the large degree of heterogeneity, more notably from a technological perspective. In this type of scenarios, the procedures which are being currently used to perform access selection (which are mostly rather static, requiring the direct participation from the end-user) are not longer valid; as an alternative, the scientific community has been recently analyzing a number of proposals to reach, as their main goal, the *Always Best Connected* paradigm, considering user preferences, network situation and service requirements. As an illustrative example of the interest that this type of schemes has recently generated, it is worth mentioning the fact that the not only the scientific community, but also the relevant standardization bodies, have paid attention to them; in fact they are working towards the specification of procedures to promote the interoperability between heterogeneous networks. In this sense, the role taken by the IEEE 802.21 group clearly outstands amongst them; it has defined [1,15] a framework to facilitate handovers between heterogenous network technologies (*Media Independent Handover Framework, MIHF*).

The main advantage of being able to use various radio technologies is that it brings about the possibility of using, any time, the most appropriate characteristic of each of them in particular moments of time; on the other hand, this also imposes a series of drawbacks, derived from the complexity which is introduced into the system, since it becomes necessary managing a larger number of parameters. In this sense, there exist a number of works which propose solutions to tackle these challenges from various perspectives. For instance, the authors of [13] present the *Common Radio Resource Management* (CRRM), which is an evolution of the *Join Radio Resource Management* (JRRM) [6], proposing a joint management of the available radio resources, assuming a complete overlap of the coverage areas of the base stations (as it is also the case in [2]), and giving the full responsibility of the resource management to the network, thus following a clearly centralized approach. Another architecture which shares many of the characteristics of the CRRM is the so-called *Multi-Radio Resource Management* (MRRM) [14], in which a feature to be distinguished is how it deals with the cooperation strategies between different operators [9]. In the same line, different algorithms have been proposed to improve the assignment of resources, considering specific parameters of the involved wireless technologies [6,16], or additionally based on micro/macro economic profiles from either the end user [7] or the network [5].

The aim of this work is to go beyond the aforementioned works by considering, not only network preferences, but also (and as the most relevant aspect) end-user ones, while managing the available radio resources. By using linear programming techniques, the goal which we pursue is twofold: on the one hand we seek the establishment of a number of upper bounds on the performance which could be achieved with this type of frameworks, thus broadening the capacity to carry out sensible comparisons between different access selection algorithms; furthermore, by defining flexible utility functions (using various parameters), we could analyze the particular configurations which might lead to better behaviors. Although the use of linear programming techniques for this type of problems might seem to be a sensible choice, there are not, to our best knowledge, many works which have explored their possibilities, as it is discussed in [4]. Some of the existing ones, e.g. [12,3,11], are based on a reduced set of parameters which are combined in the corresponding objective function, resulting on a more rigid approach. Besides, it is worth highlighting another set of existing works, which benefit from the application of *Multi-Attribute Decision Making* (MADM) techniques, see e.g. [8,17,10]. The most relevant difference comes from the fact that they can be employed with the biased information which could be acquired by individual network elements (that is, as potential access selection algorithms), since one of their advantages is their computational efficiency; however they could not probably be used so as to analyze the overall optimum performance which could be achieved by the whole networks, which is precisely the main objective of this work; in fact, based on the conclusions which could be extracted by using the framework presented in this work, we could e.g. establish the criteria to be applied while carrying out access selection procedures based on MADM.

### 3 Optimization Problem Modeling

We consider a particular network scenario, in which  $M$  access elements (either base station or access points) are deployed. We assume that each of them would have a particular RAT and an associated capacity  $\phi_j$ , as the maximum number of users they could serve. On the other hand,  $N$  end users aim at establishing a connection with one of the  $M$  access elements, since they wear devices able to use any of the involved RATs. We further assume that there are a number of different operators in the scenario, so that any of the access elements ( $j$ ) would belong to a particular operator ( $\zeta_j$ ) and each user ( $i$ ) would also have a preferred operator ( $\eta_i$ ).

We define the set of basic variables,  $x_{ij}$ , defined as:

$$x_{ij} = \begin{cases} 1 & \text{if user } i \text{ is connected with access } j \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

Starting from this basic variables, we establish a number of parameters which will be favored when carrying out the optimization process. These aspects mainly represent the preferences which an end-user might have when taking a decision about the access alternative to connect to. In particular, the parameters which are defined below will be used.

- *Connectivity.* In this case we simply model the desire of any end-user to be connected to the network, so this can be somehow seen as the basic aspect to be optimized. We will use the parameter  $\sigma_{ij}$ , defined as:

$$\sigma_{ij} = \begin{cases} 1 & \text{if user } i \in \text{coverage of access } j \\ 0 & \text{otherwise} \end{cases} \quad (2)$$

- *Preferred operator.* This parameter aims at reflecting the fact that any end-user would like to connect to an access element from his preferred operator (agreement, better prices, etc).  $\psi_{ij}$  will be used to model this parameter, defined as:

$$\psi_{ij} = \begin{cases} 1 & \text{if } \eta_i = \zeta_j \\ 0 & \text{otherwise} \end{cases} \quad (3)$$

- *Handovers.* Once an end-user is connected with an access element, he would like to maintain the connection as long as possible, so that he does not need to incur in the overhead (and degradation) associated to a handover procedure. In this sense, if the previous access element is known, we define the parameter  $\lambda_{ij}$  as:

$$\lambda_{ij} = \begin{cases} 1 & \text{if user } i \text{ was connected to access } j \\ 0 & \text{otherwise} \end{cases} \quad (4)$$

- *Link quality.* When taking a decision on the access alternative to connect to, one of the parameters which has been traditionally used is the quality of the corresponding wireless link. Obviously, this is an aspect which depends

heavily on the particular wireless technology and the selected propagation model. For the sake of generality, it can be said that it can be modeled as a decreasing function with the distance to the access element<sup>1</sup>; in this case, a simple triangle function has been used, which takes the maximum value (1) at the very same position of the access element and the minimum (0), on the edge of the corresponding coverage area, and thus  $\theta_{ij}$  is defined as:

$$\theta_{ij} = \begin{cases} 1 - \frac{d_{ij}}{\omega_j} & \text{if } d_{ij} < \omega_j \\ 0 & \text{otherwise} \end{cases} \quad (5)$$

where  $\omega_j$  is the coverage of the access element  $j$  and  $d_{ij}$  the distance to the user  $i$ .

By combining these parameters, we define a *utility* function ( $u_{ij}$ ), bringing about the possibility to establish a classification of the available access elements. As can be seen, if there is not physical connection between the end-user  $i$  and the access element  $j$  ( $\sigma_{ij} = 0$ ), the utility function is 0.0.

$$u_{ij} = [\alpha + \beta \cdot \psi_{ij} + \gamma \cdot \lambda_{ij} + \delta \cdot \theta_{ij}] \sigma_{ij} \quad (6)$$

In order to make such function as flexible as possible, each of the aforementioned aspects is modulated with a weight; as such,  $\alpha$  promotes the connectivity with any element;  $\beta$  emphasizes the connection with a preferred operator;  $\gamma$  is used to minimize the need to perform handovers; finally,  $\delta$  empowers the quality of the wireless links. By examining all the parameters introduced above, it can be seen that all of them are delimited in  $[0, 1]$ , so if we fix that the sum of the four weights equals 1.0 ( $\alpha + \beta + \gamma + \delta = 1$ ), we can also bound the utility of the connection between end-user  $i$  and access element  $j$  in the same interval. Furthermore, this can be also used to easily tweak the relevance associated to each of the parameters, bringing about the possibility to define different access selection strategies.

Taking all of the above into consideration, the goal is to solve the following optimization problem:

$$\begin{aligned} \text{Max.} \quad & \sum_{i=0, j=0}^{N-1, M-1} u_{ij} \cdot x_{ij} \\ \text{s.t.} \quad & \sum_{j=0}^{M-1} x_{ij} \leq 1 \quad i = 0 \dots N-1 \\ & \sum_{i=0}^{N-1} x_{ij} \leq \phi_j \quad j = 0 \dots M-1 \end{aligned} \quad (7)$$

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<sup>1</sup> It is worth highlighting that the goal of this work is not to accurately model the propagation model, but it focuses on the optimum selection of an access alternative. However, the implementation is flexible enough, so as the integration of more complex empirical propagation models would not impose great difficulties.

The first set of constraints fixes that an end-user can only establish a connection with just one access elements, while the second block limits the number of users connected to a particular access elements to its capacity ( $\phi_j$ ). It is important to mention that, for a particular network deployment, all the elements of the previously defined  $u_{ij}$  function exclusively depend on such scenario and thus, the only variables which need to be considered in the optimization problem are  $x_{ij}$ .

## 4 Design and Implementation of a Tool to Solve the Optimization Problem

As it has been said before, we will use the *GLPK* library to solve the problem which was presented in Section 3. This library offers an API which can be used from other application, and this eases the integration of the solver module. On the other hand the dimensions of the problem to be solved is within the limits which can be handled by this library, since the number of variables stays below  $10^4$  and, in addition, many of the corresponding coefficients (of both the objective function and the constraints) are 0.

Hence, a proprietary tool will be designed and implemented, to perform the following functionalities:

1. Read network parameters from a configuration file.
2. Deploy access elements from an external file.
3. Deploy the end-users from another external file.
4. Deploy and process the network scenario, obtaining all the parameters of the  $u_{ij}$  functions.
5. Solve the optimization problem with the *GLPK* library.
6. Process the solution.

As it was said before, one of the aspects that are considering to establish the value of  $u_{ij}$  is the previous connection of the end-user (so as to reduce, if possible, the number of required handovers). In this case, it is assumed that the position of the users varies (according to some specific mobility model) and, thus, the main programme must iterate a number of input files (*snapshots*), which reflect such mobility patterns. Each iteration must also use the solution of the previous one, so as to be able to establish the value of  $\lambda_{ij}$ .

Figure 1 depicts the high level flow diagram of the whole process.

Although the framework has been designed so that the deployment of both the access elements and the end-users could be done randomly, taking their positions from input files offers more possibilities, since it facilitates the integration with other platforms, once the format of the corresponding files has been fixed. This brings about the possibility of using the very same network deployments and movement traces, so as to foster more accurate comparisons with complementary approaches.

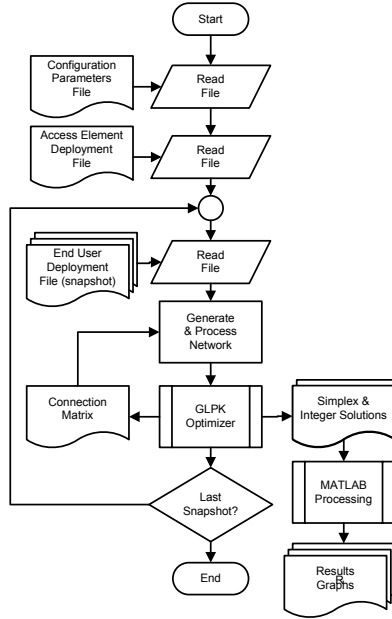


Fig. 1. Block diagram of the implemented optimization tool

## 5 Scenario Description

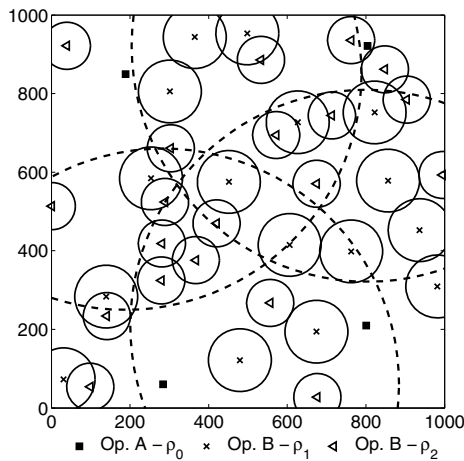
As it has been previously said, the main idea is to analyze different strategies to ensure the optimum access selection considering a heterogenous network deployment. The heterogeneity does not only extend to the involved technologies, but it also expands to the presence of various operators. In order to cover these requirements, three different access elements will be used, as can be seen in Table 1. The first one emulates a technology which could be closer to the characteristics of traditional cellular communications (e.g. GSM), since it has a notably larger coverage as well as a higher capacity. The two other access elements are clearly closer to WLAN access points, with a coverage and capacity much lower. It is important to mention that the capacity is modeled, generically, as the the maximum number of users which can be associated to the access element, e.g. without considering the subjacent traffic.

Table 1. Involved technologies

ID	Coverage ( $m$ )	Capacity	# Elements
$\rho_0$	600	20	4
$\rho_1$	80	5	16
$\rho_2$	60	5	20

We also assume that there are two different operators. The first one ( $A$ ) is the incumbent operator, and such it manages the access elements of the legacy cellular RAT ( $\rho_0$ ), while the second one ( $B$ ) would emulate novel operator, which offers a less conventional access, by means of the access elements with technologies  $\rho_1$  and  $\rho_2$ .

We consider a  $1000 \times 1000 m^2$  area, over which we randomly deploy (i.e. without any previous planning) the access element; note that we respect a minimum distance between access elements, provided that they belong to the same operator and use the same technology. Figure 2 shows the particular deployment which will be used; as can be seen, the 4 elements of RAT  $\rho_0$  cover the whole scenario, resulting in highly overlapped areas. The surface covered by operator  $B$  is remarkably lower.



**Fig. 2.** Network deployment used during the analysis

Over the same scenario, 200 users are deployed, assuming that 60% of them belong to operator  $A$ , while the others have an agreement with the less conventional operator ( $B$ ). It is further assumed that all users are able to use any of the involved technologies. All of them are randomly deployed at the beginning of the simulation, but afterwards they move according to the *Random Waypoint* model, with the characteristics which are enumerated in Table 2.

Once the scenario which will be used to carry out the analysis has been introduced, Table 3 depicts the different access selection strategies which will be studied. As can be seen, we modify the value given to the different weights, thus strengthening and prioritizing some of the different aspects which were previously discussed. In this sense strategy **A** has the only goal to maximize the number of connected users; **B** slightly favors the connections to the preferred operator and link quality, while **C** also prioritizes the reduction of the number of handovers. Strategies **D**, **E** and **F** focus (each of them) on a single parameter



**Table 2.** Characteristics of the *Random Waypoint* model used during the analysis

Characteristic	Value
Speed	$\mathbb{U}[2, 3]$ <i>m/s</i>
Movement time	$\mathbb{U}[100, 120]$ <i>m/s</i>
Pause time	$\mathbb{U}[5, 10]$ <i>s</i>
Edge policy	Reflection

**Table 3.** Analysis access selection strategies

Parameter	A	B	C	D	E	F	G
$\alpha$	1.0	0.6	0.4	0.1	0.1	0.1	0.1
$\beta$	0.0	0.2	0.2	0.9	0.0	0.0	0.0
$\gamma$	0.0	0.0	0.2	0.0	0.9	0.0	0.7
$\delta$	0.0	0.2	0.2	0.0	0.0	0.9	0.2

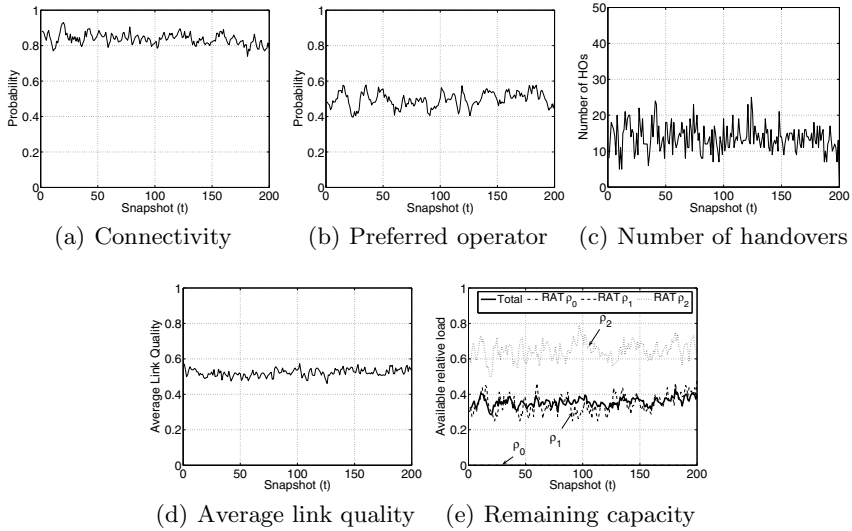
(preferred operator, number of handovers and link quality, respectively), providing a residual relevance to the connection probability. Finally, strategy **G** mainly aims at minimizing the number of handovers, but also considers link quality.

## 6 Discussion of Results

In the following we discuss the results which were obtained by using the 7 access selection strategies which have been previously presented. Each of he simulations lasts 2000 seconds, taking *snapshots* of the end-user position every 10 *s*, so the complete scenario involves the resolution of 200 optimization problems.

In order to evaluate the performance of the different alternatives, a number of metrics will be studied:

- *Connection probability.* It is the basic parameter, since it just considers whether the end-user was able to establish a connection or not.
- *Connection with the preferred operator.* It considers whether the connection was with an access element belonging to the preferred operator of the end-user.
- *Number of handovers.* It can be used to analyze the number of access element changes which must be performed.
- *Average link quality.* It averages the qualities of all the links which are established, using the function which was defined in Section 3.
- *Available load.* It is used so as to analyze the remaining capacity (for each of the involved technologies); this parameter can be used so as to determine whether more users could be accepted by the network.
- *Operator traffic.* In this case, the load accepted by each of the two operators will be analyzed, identifying the percentage of connections of users belonging to other operators, which could be used to estimate the incomes due to *roaming* circumstances.

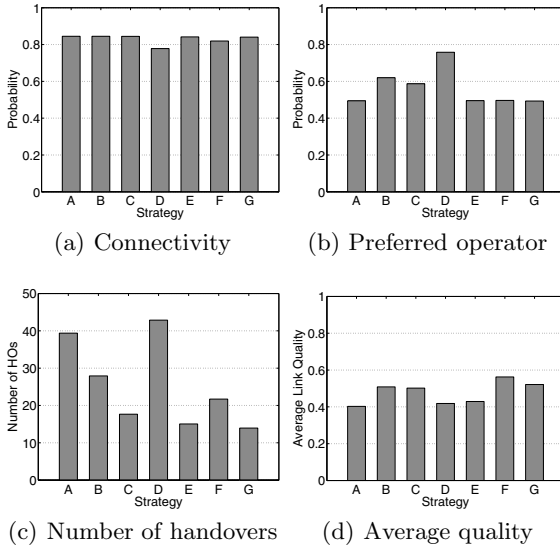


**Fig. 3.** Instantaneous variation of the different merit parameters for the access selection strategy **G**

As a first step, to ascertain the validity of the framework, we will study the instantaneous evolution of the performance of a particular strategy; this would also shed some light on the stability of the results for a single scenario (set of *snapshots* with a single movement trace). Afterwards, 10 independent runs will be executed for each of the cases, averaging the results, so as to ensure tight confidence intervals, and to be able to compare the behaviors of the 7 access selection strategies.

Figure 3 presents the connectivity probability, the percentage of connections with the preferred operator, the number of handovers, the average link quality as well as the remaining network capacity (for the various RATs) for strategy **G**. As can be seen, none of the cases presents a remarkable variation around the average behavior. Connection probability reaches a value close to 85%, while only half of the connections are with the preferred operator; it is worth recalling that in this specific access selection algorithm, the weight given to that parameter is 0, and the distribution of the end-users between the two operators (*Market Share*) tells that 60% of them are *clients* of the incumbent operator. We also observe that the parameter in which a higher variability is observed is the number of required handovers, while it stays (for this particular configuration) below 10%. Regarding the average link quality, we can see that it maintains a value rather close to 50%, with little variability around it.

What it is even more interesting is the analysis of the remaining capacity for the different access element types. It can be seen that the available capacity of the whole networks is slightly below 40%. Although it might seem weird (by looking at the connectivity results), we must take into account the fact that the



**Fig. 4.** Performance of the access selection strategies

access elements with RATs  $\rho_1$  and  $\rho_2$  have, overall, a relevant capacity (80+100), being even higher than the one offered by  $\rho_0$ , but they cover a much lower area. The consequence is that there are not enough end-users within the area covered by such RATs. In fact, the figure also allows us inferring the higher coverage of  $\rho_1$ , since the available capacity is lower than the one observed for  $\rho_2$ , whose utilization factor is rather low. Finally, we can also see that the access elements having the RAT  $\rho_0$  are fully loaded, since as was previously seen completely cover the whole area and, thus, it is quite likely that there exist some users whose only alternative is, precisely, connecting to such access elements.

Although the instantaneous results permit acquiring a preliminary idea on the behavior of the various access selection strategies, it becomes more interesting being able to compare them, so as to study their advantages and drawbacks. Eventually, if we swept all the potential combinations for the different parameters, it would be possible to establish the combination which leads to the optimum performance. In this case, we will compare the 7 alternatives which were presented in 3, carrying out, for each of them, 10 independent measurements, averaging the corresponding results.

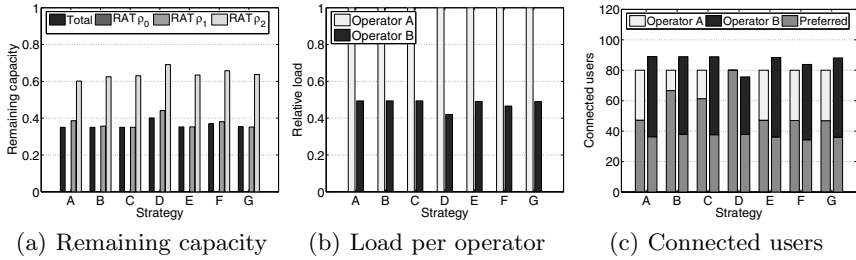
First, Figure 4(a) shows the connectivity which was observed for the 7 strategies; we can conclude that the different combinations do not have a strong influence over the achieved results, since it can be seen that in all cases, the connectivity probability is very close to 0.8. The graph yields a slight decrease in both **D** and **F** strategies (higher in the first one); by using **D** connections with the preferred operator are favored, and thus, the access elements using  $\rho_0$ , which belong to the incumbent operator, easily fill their available capacity; this, together with the fact that establishing a connection with either  $\rho_1$  or  $\rho_2$  is less

likely (since they cover a smaller area) justifies the observed decrease, which stays below 10%. The reduction is even less relevant for strategy **F** due to the fact that in this case, the connection with closer (higher quality) access elements is strengthened, thus increasing the *utility* given to  $\rho_0$  access elements.

On the other hand, we can clearly see, in 4(b), that the differences regarding the connections with non-preferred operators are much more relevant, depending on the particular access selection strategy which is being used. In those combinations in which the weight given to the  $\beta$  parameter in the utility function is 0, the probability of establishing a connection with an access element of the preferred operator does not vary (staying around 50%); we must take into account that 60% of the users are *clients* of operator which manages the access elements with a wider coverage ( $\rho_0$ ). On the other hand, by comparing the results of strategies **B**, **C** and **D** it can be inferred that the additional gain which is achieved when increasing  $\beta$  from 0.2 (in the two first ones) to 0.9 (in the last one) is, approximately, 15%; last, the connection to the preferred operator is slightly lower in strategy **C** than in **B**, since in the first one, the utility function also favors the quality of the wireless link, which slightly decreases the number of connections with the preferred operator.

Figures 4(c) and 4(d) shows the results for both the number of handovers and the average link quality for the 7 analyzed strategies. First, we can see that there exists a clear relationship between both parameters. In this sense, if we compare the results of strategies **A** and **B** (in which the  $\gamma$  parameter, weight which favors the reduction of handover events, takes the same value), we shall see that the number of handovers in the first strategy is notably higher ( $\gtrsim 25\%$ ); the reason behind this is that favoring the links with a higher quality ( $\delta = 0.2$  in strategy **B**) causes that more connections are established with closer access elements, and thus, it is less likely that a handover will be required in the following iterations. This aspect is reflected somehow if comparing strategies **E** and **G**; the first only just favors the minimization of handovers ( $\gamma = 0.9$ ), while in the second one,  $\gamma$  is reduced 20%, so as to correspondingly augment the weight given to the link quality to  $\delta = 0.2$ ; as can be seen, the consequence is that the average quality of the established connections is notably improved (around 10%), without negatively affecting the number of handovers; in fact there is a slight reduction (although the value of  $\gamma$  is lower).

Besides, Figure 5 can be used so as to analyze the influence of the different weight combinations over the available network capacity, both from the perspective of the type of RAT and operator. As it was observed before, access elements of RAT  $\rho_0$  (which match the overall capacity of operator *A*) use up all their resources, for all the strategies which have been studied. Obviously, the connectivity results (Figure 4(a)) correspond to the remaining capacity and it is strategy **D** the only one in which we observe a higher available capacity, since the access elements from operator *B* slightly reduce their occupancy. With a clear relationship with these latest results, Figure 5(c) shows the number of connected users per operator, highlighting those which are connected to their preferred operator; these results reflect the relevance of the  $\beta$  parameter, since



**Fig. 5.** Performance of the access selection strategies - capacity and load

in those strategies in which it takes a value higher than 0 (**B**, **C** and **D**), there are more users connected to their preferred operator. We shall also see that this only affects the incumbent operator, since the number of users that, being clients of *B*, can connect to their preferred operator stays unchanged (around 40 users) for all cases. The consequence is that, in strategy **D**, all users connected to operator *A* (80, which is all its overall capacity) belong to its clients, and therefore the load carried by operator *B* is reduced. Thanks to these results we could probably aim at establishing different cooperation mechanism to increase their profit, by applying different prices for the traffic coming from own clients or *roaming*.

## 7 Conclusions

This work has exhibited the possibilities that the application of linear programming techniques open in the analysis of access selection strategies, over heterogeneous network scenarios (considering both the involved technologies and the operators). We have defined an optimization problem, in which the objective function (to be maximized) can be adapted using a number of parameters which establish the different priorities that an end-user might have when deciding on access alternative amongst the others.

In order to solve the problem, we have designed and implemented an application, which is based on the *GLPK* library. Such framework has been used to study a set of access selection strategies, in which the weight given to the various parameters was modified, so as to analyze which is their influence. Using a scenario with two operators and a remarkable heterogeneity (involved radio technologies) it has been shown that there are certain combinations which offer better performances than others (at least, in terms of the number of handovers and the quality of the established wireless links). The analysis has shown, e.g. that prioritizing the choice of higher quality radio links brings about a decrease of the number of handovers. We have also analyzed the influence of the various parameters in how the load is distributed between the different types of access elements (and operators).

From the work presented in this paper, a relevant number of future research lines could be opened; first, the definition of the utility function is very flexible

so that the inclusion of new metrics within the access selection procedure or tweaking their weights could be done quite easily. This flexibility could be used e.g. to carry out a more refine variation of their values, so as to determine which is the optimum combination. Furthermore, the results obtained from this study, if we interpret them as the best that can be achieved for a particular network scenario, could be compared with complementary analysis, considering only the information (with a more local scope) that is confined to the end-user environment. Finally, we will incorporate more realistic traffic models, considering also the possibility to modify the capacity required when starting an application. Finally, we could also modify the parameters of the scenario, in terms of the market share, number of users, access element deployment, etc, so as to study their influence over the overall system performance.

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## References

1. IEEE standard for local and metropolitan area networks- part 21: Media independent handover. IEEE Std 802.21-2008 (2009)
2. Chen, B., Chan, M.: Resource management in heterogenous wireless networks with overlapping coverage. In: First International Conference on Communication System Software and Middleware, Comsware 2006 (2006)
3. Falowo, O., Anthony Chan, H.: Optimal joint radio resource management to improve connection-level qos in next generation wireless networks. In: Radio and Wireless Symposium. IEEE, Los Alamitos (2008)
4. Falowo, O.E., Chan, H.A.: Joint call admission control algorithms: Requirements, approaches, and design considerations. *Comput. Commun.* 31(6), 1200–1217 (2008)
5. Giupponi, L., Agusti, R., Perez-Romero, J., Salient, O.: Improved revenue and radio resource usage through inter-operator joint radio resource management. In: IEEE International Conference on Communications, ICC 2007 (June 2007)
6. Giupponi, L., Agusti, R., Perez-Romero, J., Sallent, O.: Joint radio resource management algorithm for multi-RAT networks. In: Global Telecommunications Conference, GLOBECOM 2005, vol. 6. IEEE, Los Alamitos (2005)
7. Giupponi, L., Agusti, R., Perez-Romero, J., Sallent, O.: WLC05-2: An economic-driven joint radio resource management with user profile differentiation in a beyond 3G cognitive network. In: Global Telecommunications Conference, GLOBECOM 2006. IEEE, Los Alamitos (2006)
8. Gu, C., Zhang, Y., Ma, W., Liu, N., Man, Y.: Universal modeling and optimization for multi-radio access selection. In: 5th International Conference on Wireless Communications, Networking and Mobile Computing, WiCom 2009 (2009)
9. Ho, L., Markendahl, J., Berg, M.: Business aspects of advertising and discovery concepts in Ambient Networks. In: IEEE 17th International Symposium on Personal, Indoor and Mobile Radio Communications (2006)

10. Hu, H., Zhou, W., Zhang, S., Song, J.: A novel network selection algorithm in next generation heterogeneous network for modern service industry. In: Asia-Pacific Services Computing Conference, APSCC 2008. IEEE, Los Alamitos (2008)
11. Karthikeyan Krishnasamy, N., Narayanasamy Palanisamy, P.: Bandwidth allocation scheme for multimedia mobile networks using optimization techniques. In: 2006 IEEE Conference on Cybernetics and Intelligent Systems (June 2006)
12. Lucas-Estan, M., Gozalvez, J., Sanchez-Soriano, J.: Common radio resource management policy for multimedia traffic in beyond 3G heterogeneous wireless systems. In: IEEE 19th International Symposium on Personal, Indoor and Mobile Radio Communications, PIMRC 2008 (September 2008)
13. Perez-Romero, J., Sallent, O., Agusti, R., Karlsson, P., Barbaresi, A., Wang, L., Casadevall, F., Dohler, M., Gonzalez, H., Cabral-Pinto, F.: Common radio resource management: functional models and implementation requirements. In: IEEE 16th International Symposium on Personal, Indoor and Mobile Radio Communications, PIMRC 2005 (2005)
14. Sachs, J., Agüero, R., Daoud, K., Gebert, J., Koudouridis, G., Meago, F., Prytz, M., Rinta-aho, T., Tang, H.: Generic abstraction of access performance and resources for multi-radio access management. In: 16th IST of Mobile and Wireless Communications Summit (July 2007)
15. Taniuchi, K., Ohba, Y., Fajardo, V., Das, S., Tauil, M., Cheng, Y.H., Dutta, A., Baker, D., Yajnik, M., Famolari, D.: IEEE 802.21: Media independent handover: Features, applicability, and realization. *IEEE Communications Magazine* 47(1), 112–120 (2009)
16. Tolli, A., Hakalin, P., Holma, H.: Performance evaluation of common radio resource management (CRRM). In: IEEE International Conference on Communications, ICC 2002, vol. 5 (2002)
17. Xing, B., Venkatasubramanian, N.: Multi-constraint dynamic access selection in always best connected networks. In: The Second Annual International Conference on Mobile and Ubiquitous Systems: Networking and Services, MobiQuitous 2005 (July 2005)