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JOINT RADIO RESOURCE MANAGEMENT IN BEYOND 3G HETEROGENEOUS WIRELESS SYSTEMS

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ABSTRACT

A key aspect of Beyond 3G heterogeneous wireless systems is the definition of Joint Radio Resource Management techniques capable to efficiently manage the radio resources from different Radio Access Technologies physically coexisting. This work proposes a set of JRRM techniques based on linear programming optimization tools that simultaneously assign to each user the adequate radio access technology and number of radio resources within such technology, to guarantee each user's quality of service demands.

I. INTRODUCTION

Beyond 3G wireless systems will be based on a variety of Radio Access Technologies (RATs) with complementary technical characteristics that will physically coexist in a seamless integrated environment. In this context, an important challenge is how to exploit in a coordinated manner the RATs radio resources to provide users with their required Quality of Service (QoS) levels while maximising each RAT system revenues. To this aim, important research activities have been conducted to define and optimise Joint Radio Resource Management (JRRM) policies, also referred as Common RRM (CRRM). JRRM techniques are in charge of deciding for each incoming call, the RAT over which it will be conveyed (RAT selection) and the number of radio resources within the selected RAT (intra-RAT RRM) that will be necessary to satisfy the user/service QoS requests. While most of the published studies separately address the RAT selection and intra-RAT RRM policies (e.g. [1] and [2]), initial proposals to jointly address them have been recently published. For example, in [3], the authors propose a JRRM algorithm based on neural networks and fuzzy logic that simultaneously determines the most appropriate RAT and bit rate allocation, although it does define intra-RRM techniques necessary to assign the radio resources needed to achieve the defined bit rate. In this context, this work proposes a set of innovative JRRM techniques based on linear programming optimization that simultaneously assigns to each user an adequate combination of RAT and number of radio resources within such RAT to guarantee the user/service QoS requirements. The potential of linear programming optimization techniques for radio resource management research was recently demonstrated in [4], where a call admission control mechanism in heterogeneous wireless networks was proposed and evaluated.

II. UTILITY FUNCTIONS

The proposed JRRM policy is based on service-dependent utility functions, established to quantify the achieved user-perceived QoS level for a given number of assigned radio resources per available RAT. Following the methodology defined in [1], this work uses the utility functions depicted in Fig. 1 for email, web and real-time video services. While web and email QoS is defined in terms of throughput, real-time video QoS considers the percentage of frames correctly transmitted before the next video is to be transmitted. Paper length restrictions do not allow for a detailed explanation of how the utility functions were created, however, the authors already demonstrated in [1] the capability of these utility functions to adequately reflect the user needs. To define the utility functions, three QoS levels and their corresponding utility values were established. It is important to note that utility values above zero have only been assigned when the minimum QoS request is satisfied. This will result in that radio resources are not assigned to users if they cannot provide at least the established minimum QoS level.

After establishing the utility functions, it is then necessary to relate radio resources and utility values. To this aim, a transmission rate is selected per radio resource in each RAT. It is important to note that all emulated RATs implement Adaptive Modulation and Coding (AMC) resulting in varying transmission modes and rates as channel quality varies. In this scenario, transmission modes providing a balance between data rates and error correction have been chosen to define such relation. In particular, average data rates of 13.4 kbps (corresponding to the coding scheme CS2) and 22.4kbps (corresponding to the modulation and coding scheme MCS5) per timeslot have been selected in GPRS and EDGE, respectively. In HSDPA, various transmission modes can be defined for a given number of assigned codes. In this case, the transmission mode providing a balance between data rates and error correction has also been considered. Once the average data rate per radio resource in all possible RATs has been selected, the relation between utility values and radio

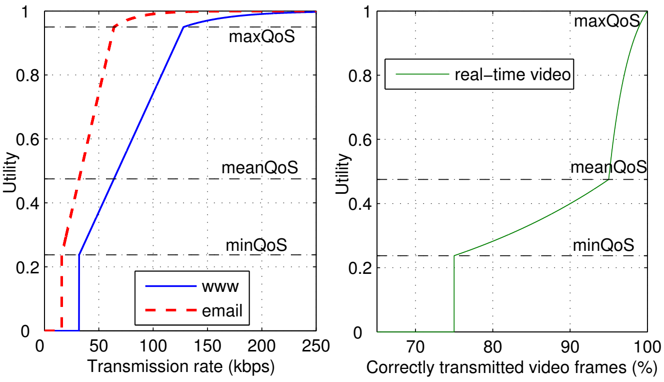

Figure 1: Utility functions per traffic service.

resources can be directly established for web and email users. For real-time H.263 video users, an additional step is necessary to compute the data rate needed for real-time operation, i.e. to ensure that each video frame is correctly transmitted before the next one must be sent. To this aim, the cumulative distribution function of the throughput necessary to transmit each video frame before the next one is to be sent was extracted using a real-time H.263 video model [1]. Table 1 shows an example of the relation between utility values and the number of radio resources per selected RAT for real-time 64 kbps H.263 video users; the RAT/resources combination are shown in increasing throughput order. The resources/RAT combination is denoted as *xY*, corresponding to *x* radio resources from RAT *Y* (GPRS is represented as *G*, EDGE as *E*, and HSDPA as *H*). As previously mentioned, it is interesting to note that utility values different from zero are not defined until the RAT/resources combination can achieve the established minimum QoS level. Also, once the maximum QoS level has been achieved, the utility value does not augment despite increasing throughput capabilities.

Table 1: 64 kbps video utility values.

Res./ RAT	Data rate (kbps)	Utility value	Res./ RAT	Data rate (kbps)	Utility value	Res./ RAT	Data rate (kbps)	Utility value
1G	13.4	0.00	4E	89.6	0.298	3H	741	1.00
1E	22.4	0.00	7G	93.8	0.313	4H	1139.5	1.00
2G	26.8	0.00	8G	107.2	0.353	5H	2332	1.00
3G	40.2	0.00	5E	112	0.365	7H	4859.5	1.00
2E	44.8	0.00	1H	116.5	0.378	8H	5709	1.00
4G	53.6	0.00	6E	134.4	0.435	10H	7205.5	1.00
5G	67	0.00	7E	156.8	0.934	12H	8618.5	1.00
3E	67.2	0.00	8E	179.2	0.982	15H	11685	1.00
6G	80.4	0.00	2H	396	1.00			

III. LINEAR PROGRAMMING JRRM PROPOSAL

A. JRRM objective function

The proposed JRRM technique is aimed at providing the highest possible homogeneous user satisfaction levels to all service types by exploiting the QoS/resource flexibility offered by different services present in a multimedia framework. In fact, achieving a similar user satisfaction level, here represented by utility values, does not require the same number of radio resources or capabilities for different service types. In this context, the proposed JRRM objective function can be denoted as follows:

$$\max\{\min u_j\}, j \in [0, N-1] \quad with \quad u_j = \sum_r \sum_s u_j^r\left(s^r\right) \cdot y_j^{r,s} \qquad (1)$$

where u_j represents the utility value assigned to user *j* in a combined RAT/resources distribution round, and *N* corresponds to the total system user load. When defining u_j, $u^r_j(s^r)$ represents the utility value obtained by user *j* when assigned *s* radio resources (codes or timeslots) of RAT *r* (*r* is equal to 0, 1 or 2 for GPRS, EDGE and HSDPA respectively), and $s \in [1, c_r]$ with c_r corresponding to the maximum number of radio resources available at each RAT. $y_j^{r,s}$ is a binary variable equal to one if user *j* is assigned *s* radio resources of RAT *r*, and equal to zero if not. Given that we have considered that users can only receive resources from one RAT, only one $y_j^{r,s}$ variable can be equal to one for each user. When distributing RAT/resources among requesting users, the proposed JRRM policy must establish the values for the $y_j^{r,s}$ variables, considering that only $y_j^{r,s}$ variables achieving a utility value greater than zero are allowed, i.e. resources are not assigned to a user if they would not achieve the user minimum QoS level.

In order to apply linear programming techniques to solve the established problem, (1) must be expressed as a linear equation. To this aim, a new real variable denoted as *z* and equal to the smaller utility value assigned to a user has been defined, which results in the following objective function:

$$\max\ z,\ j \in [0, N-1] \quad with \quad z \le u_j \qquad (2)$$

B. JRRM constraints

Once the basic objective function has been established, the problem statement can be completed with some system and service constraints. If a high system load cannot guarantee that all users are granted their minimum QoS requests, the problem could have no solution. To avoid this situation, it has been imposed that one $y_j^{r,s}$ variable must be equal to one for each user. When such constraint cannot be reached, the number of users requesting resources will be reduced so that:

$$\sum_r \sum_s y_j^{r,s} = 1, \forall j \quad and \quad \sum_j \sum_{s^r} s^r \cdot y_j^{r,s} \le c_r, \forall r \qquad (3)$$

Whenever a user requests resources for a new transmission or a given transmission ends, the proposed JRRM policy is applied. In this case, only real-time video active users that were assigned resources in the previous JRRM distribution round maintain those corresponding to their minimum QoS level and compete for additional resources with the other users, which can be expressed as:

$$\sum_r \sum_{s^r} E_{s^r} \cdot y_j^{r,s} \ge E_{\min}, \forall j_{h263} \qquad (4)$$

where E_{s^r} represents the RAT/resources combination index in the utility tables (e.g. Table 1) for the assignment of *s* radio resources in RAT *r*. Similarly, E_{min} represents the index of the RAT/resources combination achieving the minimum QoS level.

In case the available resources do not allow achieving equal utility values for all users, users are served based on the following service priority: real-time H.263 video (higher priority), web, and email; real-time video users with higher video bit rates are served first. If the lowest priority user (*m*) is a video user that obtained radio resources in the previous JRRM distribution round, the condition established in (4) comes first and the video user would be assigned the s_{min} radio resources from RAT r_{min} necessary to achieve its minimum QoS level defined by E_{min}.

When such level is achieved, the lowest priority user will not be assigned additional resources until the highest priority user (k) surpasses its utility value ($u_m^{r_{\min}}(s_{m_{\min}})$), expressed as:

$$\sum_{r_a}\sum_{s_a} u_m^{r_{\min}}\left(s_{m_{\min}}\right)\cdot y_k^{r,s} + \sum_{r_b}\sum_{s_b} u_k^{r}\left(s^{r}\right)\cdot y_k^{r,s} \geq \sum_{r}\sum_{s} u_m^{r}\left(s^{r}\right)\cdot y_m^{r,s} \tag{5}$$

where (r_a,s_a) represent the RAT/resources assignments that verify $u_m^{r_{\min}}\left(s_{m_{\min}}\right)-u_k^{r_a}\left(s_a\right)>0$ and (r_b,s_b) the assignments that verify $u_m^{r_{\min}}\left(s_{m_{\min}}\right)-u_k^{r_b}\left(s_b\right)\leq 0$; this condition is only applied when the priority of user k is higher than that of user m. Following (5), if active users cannot obtain their minimum QoS demand (it is not possible to satisfy (3)) and the linear objective function does not have a solution, users with the lowest priority will be eliminated from the JRRM distribution round until the present users and their demand allow for a linear programming JRRM solution to be achieved.

C. *Linear programming resolution*

Linear programming tools are widely employed in optimization problems. Following the previously defined linear objective function, this work proposes the use of linear programming tools to solve the defined JRRM problem characterized by the binary and real unknown variables $y_j^{r,s}$ and z. Given its performance and computational properties, one of the most commonly used approaches to solve Mixed Integer Programming (MIP) problems, such as the one defined in the previous section for JRRM, is the Branch and Bound method [5]. This technique solves an ordered sequence of reduced linear programming problems until an optimum solution is achieved. Such reduced linear programming problems are obtained when the condition that the unknown variable must be an integer one is relaxed, and real variables are allowed. To solve such reduced linear programming problems, this work proposes to use the simplex method [5], which is regularly employed in problems with a large number of variables and that require computationally efficient solutions, as in the case of real-time mobile and wireless communication systems. The interested reader is referred to [5] for additional details on the simplex, and Branch and Bound methodologies. To solve the defined MIP problem, this work has used the optimization software ILOG CPLEX, which is widely employed by companies to improve their decision-making processes.

IV. PERFORMANCE AND OPTIMISATION

The performance of the proposed JRRM technique has been evaluated in a multi-RAT and multimedia wireless platform emulating GPRS, EDGE and HSDPA. In terms of service distribution, email, web and real-time video transmissions represent each one third of the total user load; real-time H.263 video users are equally distributed among three different bit rates selected from the emulated ones: 16, 64, 128, 256 and 512kbps. A single cell with equal GPRS, EDGE and HSDPA coverage is modelled, and two multimedia traffic scenarios have been emulated. While the first scenario (E1), emulates web, email and real-time H.263 video transmissions at 16, 64 and 128kbps bit rates, the second one (E2) considers real-time H.263 video users with 64, 256 and 512kbps video bit rates. For both scenarios, cell loads of 10, 20 and 30 users have been simulated with one frequency carrier each (i.e. eight timeslots) for GPRS and EDGE, and 14 HSDPA codes.

A. *Original JRRM proposal*

Table 2 shows the percentage of users per service class that following the JRRM implementation and execution achieved the utility values corresponding to the minimum, medium and maximum QoS levels previously defined. Maximum QoS levels cannot be achieved under all emulated scenarios since radio resources demand surpasses resources availability for the emulated scenarios. Table 2 shows that the implemented JRRM policy achieves its objectives, i.e. that all services obtain the highest and most homogeneous possible QoS levels, and that service priorisation effects are most notable when the load increases. Under high loads, homogeneous QoS levels cannot be achieved across all service types. In fact, a percentage of video users received the radio resources corresponding to their maximum QoS level, while a high percentage of email users did not even received the resources needed to satisfy their mean QoS demand. This is due to the fact that if low priority users, such as email, received the resources initially assigned to higher priority users to pass from their mean QoS level to their higher one, they will obtain a utility value (or QoS satisfaction) higher than that achieved by video users; this possibility is not allowed by the JRRM policy since it will not comply with the service priorisation constraint.

To better understand the operation of the proposed JRRM policy, it is interesting to analyse the JRRM resources distribution as the load or service QoS requirements change. To this aim, we will consider as an example the 64 kbps video service radio resource assignments. Under low radio resources demands, users tend to receive the RAT/resources

Table 2: JRRM performance (in %) per service class.

	E1 - 10 users			E2 - 10 users		
	minQoS	meanQoS	maxQoS	minQoS	meanQoS	maxQoS
email	100	99.98	88.31	99.73	97.60	59.52
www	100	99.99	89.18	99.91	98.91	68.55
lower-rate video	100	100	99.66	100	97.04	88.34
mean-rate video	100	100	99.55	99.95	98.97	98.97
higher-rate video	100	100	100	100	96.85	96.85
	E1 - 20 users			E2 - 20 users		
	minQoS	meanQoS	maxQoS	minQoS	meanQoS	maxQoS
email	89.62	25.08	0.16	59.56	10.20	0.065
www	99.08	89.06	1.85	91.15	67.54	1.12
lower-rate video	100	99.30	76.43	99.83	79.26	65.95
mean-rate video	100	87.66	86.76	99.65	91.26	91.26
higher-rate video	100	100	100	99.90	86.88	86.88
	E1 - 30 users			E2 - 30 users		
	minQoS	meanQoS	maxQoS	minQoS	meanQoS	maxQoS
email	8.26	0.002	0.0	4.39	0.0	0.0
www	76.01	53.75	0.001	59.20	29.86	0.003
lower-rate video	100	94.24	54.94	99.12	55.46	47.75
mean-rate video	99.99	88.44	88.33	98.62	79.97	79.97
higher-rate video	99.98	99.98	99.98	99.60	74.02	74.02

combinations achieving their maximum QoS request. For example, 3.9% and 95.6% of 64kbps video transmissions were assigned 8E and 2H under the E1 scenario with 10 users load per cell; 8E and 2H result in utility values equal to 0.9819 and 1 respectively (see Table 1). When the cell load or service QoS requirements increase, the JRRM policy adjusts the RAT/radio resources distributions to that guaranteeing the minimum and mean QoS requirements to the higher possible percentage of users. For example, when increasing the load to 20 users in E1, 11.8%, 1.7% and 85.1% of the 64kbps video transmissions are assigned 1H, 8E and 2H radio resources respectively, thereby demonstrating the capacity of the proposed JRRM technique to adapt its resources distribution decisions to the specific operating conditions.

Despite its performance, Table 3 shows that in some cases a high percentage of radio resources where not assigned by the JRRM policy (first column)[1]. This can be due to several reasons, for example, the fact that maximum QoS demands are satisfied for all users that thereby do not require additional resources; this is for example the case for the 10 users cell load scenarios. Another reason that explains the unused radio resources is that when the number of available radio resources is lower than the total user demands, the JRRM policy had to eliminate the lower priority users from the resources distribution; this was needed to achieve a solution with the linear programming optimization tools. It can be possible that the last eliminated user had a resources demand higher than that of all previously eliminated users, thereby representing the only reason why a solution could not be initially reached. In this case, it is possible that users that could have been satisfied with low performance resources do not receive any radio resources, and such low performance resources are left unassigned since remaining users need higher performance radio resources to satisfy their QoS demands and, in addition, they cannot receive resources from various RATs. This factor was the main one to explain the unused radio resources under the 30 users load scenarios. A final reason explaining the unused radio resources, is the fact that when the maximum is achieved for the minimum utility value assigned to a user (variable z), the other users that obtained higher utility values stop competing for additional radio resources that could further improve their QoS satisfaction levels.

Table 3: Percentage of JRRM distributions that do not assign all available radio resources

	E1		E2	
	Not all resources	Users with 0 resources	Not all resources	Users with 0 resources
10 users	77.82	0.0	81.64	0.78
20 users	50.70	18.03	40.50	43.16
30 users	32.62	100	43.34	100

B. *JRRM variants*

To overcome the limitations of the original JRRM policy, three different variants are proposed and evaluated. In the first one, after the original JRRM distribution is completed, iterative JRRM distributions are performed considering only the unused radio resources and the users that did not receive any radio resources after the original JRRM distribution. Table 4 shows that this JRRM variant increases the QoS to the lower priority users, especially to emails users, without modifying the QoS experienced by the remaining users. This improvement is due to a more efficient radio resources allocation that decreases the percentage of resource distributions over which radio resources are left unassigned (see Table 5). Such decrease is particularly important for high cell loads, whereas no significant difference is observed between the original JRRM policy and its variant under low cell loads. Although under certain distribution rounds some resources were left unassigned while some users did not receive any radio resources, it is important to note that in all cases the unassigned resources were not sufficient to provide the user requested minimum QoS level.

When the number of available radio resources was lower than the total user demands, the original JRRM policy sequentially eliminated from the resources distribution the lower priority users until a feasible solution could be achieved. It is important to note that due to the established priorisation policy and the service QoS demands, the users that are first eliminated are generally the ones with the lower resource requirements. On the other hand, the users that are lastly eliminated before reaching a feasible solution are the ones with the higher resources demand, and the main cause why the linear programming tools could not reach a feasible solution. This process resulted in that certain low priority users that could have been served with the available radio resources were not assigned any. To overcome this inefficiency, the second JRRM variant first performs the

Table 4: First variant performance (in %) per service class.

	E1 - 20 users			E2 - 20 users		
	minQoS	meanQoS	maxQoS	minQoS	meanQoS	maxQoS
email	90.16	25.25	0.33	62.53	11.03	0.89
www	99.15	89.13	1.88	93.40	69.2	1.38
lower-rate video	100	99.30	76.43	99.96	79.28	65.97
mean-rate video	100	87.66	86.76	99.65	91.26	91.26
higher-rate video	100	100	100	99.90	86.88	86.88
	E1 - 30 users			E2 - 30 users		
	minQoS	meanQoS	maxQoS	minQoS	meanQoS	maxQoS
email	10.27	0.1	0.098	7.97	0.07	0.7
www	77.10	54.82	0.021	64.12	33.52	0.02
lower-rate video	100	94.24	54.94	99.88	55.53	47.82
mean-rate video	100	88.44	88.33	98.10	79.88	79.87
higher-rate video	99.98	99.98	99.98	99.6	73.98	73.99

Table 5: Percentage of distributions for the first JRRM variant that do not assign all available radio resources

	E1		E2	
	Not all resources	Users with 0 resources	Not all resources	Users with 0 resources
10 users	77.82	0.0	81.40	0.0
20 users	47.66	12.55	23.70	0.34
30 users	9.82	100	0.60	100

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[1] The second column in Table 2 corresponds to the percentage of JRRM distributions over which radio resources were left unassigned and some users didn't receive any. For example in the E1 scenario with 20 users load, 50.7% of JRRM distributions resulted in some radio resources being unassigned. In 18% of such cases, there were users that didn't receive any radio resource.

original JRRM distribution process. If resources are left unassigned while some users have not received any, the second JRRM variant identifies out of these under-served users the ones with the higher resources demands that blocked the possibility to find a feasible resources distribution solution with the original JRRM policy. These users are then eliminated, and a second JRRM distribution process is performed with the remaining under-served users and the originally unassigned radio resources. The direct comparison of Tables 2 and 6 shows that the second variant is again capable to improve the performance of lower priority users with respect to the original JRRM scheme without reducing the other user's performance. It is also interesting to note that the second JRRM variant outperforms the first one with respect to email users. On the other hand, the first variant achieves the higher web performance improvements.

Table 6: Second variant performance (in %) per service class.

	E1 - 20 users			E2 - 20 users		
	minQoS	meanQoS	maxQoS	minQoS	meanQoS	maxQoS
email	89.89	25.27	0.35	65.19	13.44	3.07
www	99.08	89.06	1.85	91.31	67.55	1.12
lower-rate video	100	99.30	76.42	99.93	79.26	65.95
mean-rate video	100	87.66	86.76	99.65	91.26	91.26
higher-rate video	100	100	100	99.89	86.93	86.93
	E1 - 30 users			E2 - 30 users		
	minQoS	meanQoS	maxQoS	minQoS	meanQoS	maxQoS
email	11.36	1.55	1.54	15.20	5.28	5.16
www	76.01	53.75	0.001	59.73	29.91	0.003
lower-rate video	100	94.24	54.94	99.60	55.48	47.77
mean-rate video	100	88.44	88.33	98.62	79.89	79.89
higher-rate video	99.98	99.98	99.98	99.60	74.02	74.02

As it was previously explained, it is possible that radio resources are left unassigned with the original JRRM scheme once the maximum possible value for the z variable is achieved. To avoid this inefficiency, the third JRRM variant modifies the objective function as follows:

$$\max\,(z + 0.001 \cdot \sum_{j} u_j), \quad j \in [0, N-1] \cdot \tag{6}$$

The second term in (6) represents the sum of the utility values achieved by all users participating in the JRRM resources distribution, pondered by a low value factor. This second term results in that the resources distribution does not stop when the maximum z value is reached. The low pondering factor has been chosen to guarantee that the second term in (6) does not influence the original JRRM distribution results until the maximum z value is achieved. The comparison of Tables 2 and 7 shows that the third JRRM variant also improves the performance with respect to the original JRRM proposal. However, important differences can be found between the first two variants and this third one. With the first two JRRM variants, unassigned resources were mainly distributed among lower priority users, thereby significantly improving the percentage of users achieving their minimum QoS requirements. On the other hand, the third proposed JRRM variant distributes unassigned resources among all service types, in particular among those that already received resources in the original JRRM distribution process. Although this procedure mainly benefits web and video users, the third JRRM variant can also improve the minimum QoS performance, in particular when the load and service requirements increase. Finally, Table 8 illustrates the efficiency of the third proposed JRRM variant in distributing the available radio resources.

Table 7: Third variant performance (in %) per service class.

	E1 - 20 users			E2 - 20 users		
	minQoS	meanQoS	maxQoS	minQoS	meanQoS	maxQoS
email	89.29	28.96	0.20	61.00	11.62	0.08
www	99.05	89.59	6.39	91.77	68.25	4.18
lower-rate video	100	99.36	88.62	99.97	80.32	71.31
mean-rate video	100	91.88	90.93	99.65	94.65	94.65
higher-rate video	100	100	100	99.90	94.62	94.62
	E1 - 30 users			E2 - 30 users		
	minQoS	meanQoS	maxQoS	minQoS	meanQoS	maxQoS
email	8.34	0.07	0.0	6.76	0.0	0.0
www	75.81	52.42	0.04	60.52	29.94	0.04
lower-rate video	100	94.76	86.13	99.75	57.23	56.64
mean-rate video	100	9.42	94.15	98.64	85.81	85.81
higher-rate video	99.98	99.98	99.98	99.6	86.06	86.06

Table 8: Percentage of distributions for the third JRRM variant that do not assign all available radio resources.

	E1		E2	
	Not all resources	Users with 0 resources	Not all resources	Users with 0 resources
10 users	45.82	0.0	40.68	0.0
20 users	0.24	16.67	0.34	17.65
30 users	1.02	100.0	0.60	100

V. CONCLUSIONS

This paper presents a set of JRRM policies designed to jointly manage the available RATs and their corresponding radio resources in heterogeneous wireless networks. The proposed JRRM schemes are based on linear programming optimization tools and QoS service differentiation in multimedia traffic scenarios. The obtained results not only demonstrate the interesting performance of the proposed JRRM techniques, but also their capability to adapt their resource assignments to the specific system conditions and service QoS demands.

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