Improved Joint Resource and Power Allocation Algorithm with QoS Provisioning

Diego A. Sousa, Weskley V. F. Maurício, Roberto P. Antonioli, Tarcisio F. Maciel, F. Rafael M. Lima

***Abstract*— This work revisits the resource and power assignment problem of maximizing the spectral efficiency of a wireless system subject to user satisfaction constraints in multi-service scenarios. Two limitations of the state-of-the-art solution are shown, which are: 1) the use of estimated throughput to determine the priority between user equipments; and 2) infeasible solutions are not treated. Thus, two improvements to deal with those limitations are proposed without increasing the computational complexity. Simulation results show that the algorithm with the proposed improvements achieves better performance and deals with infeasible solutions.**

***Keywords*— Multi-service, quality of service (QoS), rate maximization, resource and power assignment.**

I. Introduction and Literature Review

Over the last decades, mobile communications experienced an incredible development moving from the analog voice-only First Generation (1G) of cellular systems to the commercial deployment of digital multimedia Fourth Generation (4G) networks in several countries. Currently, Fifth Generation (5G) networks are the target of intense research in the industrial and academic areas [1]. The main motivations for the development of this technology is the search for better Quality of Service (QoS), Quality of Experience (QoE), lower latency, higher data rates, new (multimedia) services, higher Energy Efficiency (EE) and evolution/massification of the digital technology with more powerful devices. The novel systems promise to meet data traffic requirements that increase at large rates since more and more devices will be connected to future mobile systems.

In order to cope with this challenging scenario, technological advances in architecture and radio access technologies must be able to meet the foreseen requirements. We highlight Radio Resource Allocation (RRA) as one of the most important features of mobile networks. RRA consists in a set of functionalities that are able to optimize the performance of the mobile networks. In this paper, we employ RRA algorithms to manage the scarce radio resources such as power and frequency bands. These features have been successfully used to optimize mobile networks in terms of spectral efficiency, QoS provision, and increased capacity [2].

Many works have addressed RRA for point-to-multipoint Orthogonal Frequency Division Multiple Access (OFDMA) networks problems with different objectives and solutions. For example, the MaxRate-MinReq problem was solved by means of meta heuristics in [3] and using an exact solution in [4]. In [3], authors use Particle Swarm Optimization to perform subcarrier and power allocation. In [4], the authors transform a Mixed Integer Non-Linear Problem into a Mixed Integer Linear Problem to obtain an exact solution. However, the proposed algorithm by [4] has a high computational complexity which makes it difficult to use it in practical networks where resource allocation is expected to change within few milliseconds.

Note that none of the previous works presented so far in this section have addressed multi-service scenarios with satisfaction guarantees. In [5], we extended the problem of [6] to evaluate the performance gains that can be achieved with the joint optimization of adaptive power allocation and frequency resource assignment, and a low complexity suboptimal algorithm was proposed. Although the solution from [5] achieves good performances, two limitations are present in the algorithm: 1) the use of estimated throughput to determine the priority between User Equipments (UEs); and 2) infeasible solutions are not treated. Therefore, in this paper we propose two improvements in the algorithm proposed in [5], allowing us to deal with infeasible solutions and achieve a better performance.

II. System Modeling

Considering the downlink of a cellular system composed of a number of sectored cells. For a given sector of a cell, there is a group of UEs connected to the cell's Base Station (BS). The system combines OFDMA and Time Division Multiple Access (TDMA) and its available resources are arranged in a frequency-time resource grid. We denote Resource Block (RB) as the minimum allocable resource that is defined as a group of adjacent subcarriers and a number of consecutive Orthogonal Frequency Division Multiplexing (OFDM) symbols in the time domain, which represents the Transmission Time Interval (TTI). The UEs of a sector can be simultaneously served by the assignment of different orthogonal frequency-time RBs and, therefore, there is no intra-cell interference among UEs of the same sector. It is worth mentioning that the analyses performed in this study are also useful for other wireless multiple access schemes capable of assuring no intra-cell interference.

We consider the simplified assumption that the inter-cell interference is added to the thermal noise in the Signal to Noise Ratio (SNR) expression. We highlight that this assumption becomes more and more valid as the number of BSs in the system and their loads increase [7]. Basically, as the number

The authors belong to the Wireless Telecomunnications Research Group (GTEL), Federal University of Ceará, Fortaleza, Brazil. F. Rafael M. Lima is also with Federal University of Ceará, campus Sobral. Emails: {diego,weskley,antonioli,maciel,rafaelm}@gtel.ufc.br

Diego A. Sousa is also with Federal Institute of Education, Science, and Technology of Ceará, Paracuru, Ceará, Brazil.

The authors would like to thank FUNCAP, CAPES and CNPq for their financial and scholarship support.

of interference sources increase, the central limit theorem can be applied. It is important to emphasize that our single-cell approach can be directly applied in multi-cell scenarios where the inter-cell interference can be predicted with acceptable confidence. As interference can be estimated, transmission data rates can also be estimated before resource allocation.

In a given TTI, J active UEs are candidates to get RBs. We assume that there are N available RBs. Moreover, $\mathcal{J}$ and $\mathcal{N}$ are the set of active UEs and available RBs, respectively. As we are dealing with a multi-service scenario, we assume that the number of services provided by the system operator is S and that $\mathcal{S}$ is the set of all services. We consider that the set of UEs from service $s \in \mathcal{S}$ is $\mathcal{J}_s$ and that $|\mathcal{J}_s| = J_s$, where $|\cdot|$ denotes the cardinality of a set in this context. When this operator is used in a scalar, it denotes its absolute value. Note that $\bigcup_{s\in\mathcal{S}} \mathcal{J}_s = \mathcal{J}$ and $\sum_{s\in\mathcal{S}} J_s = J$.

Assuming that the RB n is assigned to UE j, the received SNR $\gamma_{j,n}$ of UE j on RB n is given by

$$\gamma_{j,n} = \frac{\alpha_j \; p_n \; |h_{j,n}|^2}{\sigma_j^2}, \tag{1}$$

where α_j models the joint effect of path gain and long-term fading experienced in the link between BS and UE j, $h_{j,n}$ is the short-term frequency response of the channel experienced by UE j on RB n, σ_j^2 is the noise power at UE j and p_n is the power allocated on RB n.

We assume that there are M possible Modulation and Coding Schemes (MCSs) levels to transmit and, therefore, M possible non-zero transmit data rates per RB where v_m represents the transmit data rate corresponding to the m^{th} MCS level. $\mathcal{M} = \{1, 2, \cdots, M\}$ is the set of all MCSs. Note that the m^{th} MCS level is employed when the estimated SNR is between γ_m and γ_{m+1} with $\gamma_m < \gamma_{m+1}$.

Without loss of generality, we assume a Block Error Rate (BLER)-based link adaptation where for a given SNR, the chosen MCS level is the one with the highest transmit data rate that assures an estimated BLER lower than a given fixed BLER target. Accordingly, depending on the SNR interval, different transmit data rates can be achieved.

Notice that, since discrete MCSs are employed, the transmit power can also be modeled as a discrete variable. As previously commented, the BLER-based link adaptation mechanism can select the MCS used in the transmission based on SNR regions. Therefore, it is reasonable that the transmit power should be set to the minimum value that is capable to achieve the SNR that fulfills the BLER requirement. Considering UE j and RB n, we define $\lambda_{j,n,m}$ as the minimum transmit power that should be allocated to UE j on RB n so as to employ the MCS m. Specifically, $\lambda_{j,n,m}$ is given by

$$\lambda_{j,n,m} = \frac{\gamma_m \; \sigma_j^2}{\alpha_j \; |h_{j,n}|^2}. \tag{2}$$

Therefore, we can introduce $\mathbf{Y}$ as a $J \times N \times M$ assignment matrix with elements $y_{j,n,m}$ that assume the value 1 if RB n is assigned to UE j and the transmission is configured with the m^{th} MCS level. In this case, the allocated power to the RB n assigned to UE j is equal to $\lambda_{j,n,m}$ given by equation (2). The assignment matrix $\mathbf{Y}$ is the optimization variable of the studied problem. The total available power at the BS is P^{tot}.

III. State of the art Problem

Let us assume that, at the current TTI, UE j has a data rate requirement equal to t_j. It is important to mention here that long-term data rate requirements can be mapped to instantaneous data rate requirements [8]. The minimum satisfaction constraint for each service is represented by the parameter k_s which is the minimum number of UEs from service s that should be satisfied. We assume that the index of UEs in $y_{j,n,m}$, $r_{j,n}$ and in t_j are sequentially disposed according to the service, i.e., the UEs from $j = 1$ to $j = J_1$ are from service 1, UEs from $j = J_1 + 1$ to $j = J_1 + J_2$ are from service 2, and so on.

The problem considered in this work is the one presented in [5]. This problem can be mathematically written as

$$\max_{y_{j,n,m}} \sum_{j\in\mathcal{J}} \sum_{n\in\mathcal{N}} \sum_{m\in\mathcal{M}} v_m \cdot y_{j,n,m}, \tag{3a}$$

$$\text{s.t.} \sum_{j\in\mathcal{J}} \sum_{m\in\mathcal{M}} y_{j,n,m} \leq 1, \; \forall n \in \mathcal{N}, \tag{3b}$$

$$\sum_{j\in\mathcal{J}} \sum_{n\in\mathcal{N}} \sum_{m\in\mathcal{M}} y_{j,n,m} \cdot \lambda_{j,n,m} \leq P^{\text{tot}}, \tag{3c}$$

$$\sum_{n\in\mathcal{N}} \sum_{m\in\mathcal{M}} v_m \cdot y_{j,n,m} \geq \rho_j \, t_j, \; \forall j \in \mathcal{J}, \tag{3d}$$

$$\sum_{j\in\mathcal{J}_s} \rho_j \geq k_s, \quad \forall s \in \mathcal{S}, \tag{3e}$$

$$y_{j,n,m} \in \{0, 1\}, \; \forall j \in \mathcal{J}, \forall n \in \mathcal{N} \text{ and } \forall m \in \mathcal{M}, \tag{3f}$$

$$\rho_j \in \{0, 1\}, \quad \forall j \in \mathcal{J}, \tag{3g}$$

where ρ_j as a binary selection variable that assumes the value 1 if UE j is selected to be satisfied and 0 otherwise.

The objective function shown in (3a) is the total downlink data rate transmitted by the BS. The first constraints (3b) assure that an RB will not be shared by different UEs, i.e., there is no intra-cell interference. The constraint (3c) assures that the total used transmit power is not higher than the total available power P^{tot} at BS. The QoS constraints are modeled in (3d) and (3e) assuring that a minimum number of UEs should be satisfied for each service.

A. State of the art algorithm

The state-of-the-art low-complexity algorithm that addresses the problem described in Section III was proposed in [5], and is further referred in this paper as Joint RB Assignment and Power Allocation (JRAPA) algorithm. The JRAPA algorithm in turn was inspired by the Reallocation-based Assignment for Improved Spectral Efficiency and Satisfaction (RAISES) heuristic [6]. The first step of the JRAPA algorithm is to select which UEs will compete for resources in the next steps of the heuristic. The criterion adopted is to select the k_s UEs with the highest ratio between average throughput over the RBs and rate requirement, for each service $s \in \mathcal{S}$. The JRAPA heuristic estimates the average throughput by considering the mean SNR over all the RBs of each UE. Moreover, since the power is also a resource that should be allocated by the RRA algorithm, it is also considered by [5] that the power is equally divided among all the RBs. In other words, the algorithm proposed by [5] selects the k_s UEs with highest priority $\overline{r}_j$, given by

$$\overline{r}_j = f\left(\frac{\frac{P^{\text{tot}}}{N}\cdot\frac{\sum_{n\in\mathcal{N}}\left(\alpha_j.|h_{j,n}|^2\right)}{N}}{\sigma_j^2}\right). \tag{4}$$

for $j \in \mathcal{J}_s$, for all services $s \in \mathcal{S}$.

Once the UEs that should be satisfied by the JRAPA algorithm are selected, an initial RB assignment is performed. Firstly, the JRAPA algorithm estimates the minimum amount of RBs that each UE should receive, considering that the RBs will be able to transmit at the maximum MCS. In other words, the minimum number of RBs that each UE should receive is given by $\lceil t_j/v^M \rceil$. Iteratively, the algorithm selects the UE j with the lowest priority $\overline{r}_j$ that should be satisfied and has not received the minimum number of RBs. Then, the algorithm allocates to that UE j the best RB that was not yet assigned. The initial assignment stops when all UEs that should be satisfied receive the estimated minimum number of RBs or all RBs have already been assigned. If the later condition is firstly achieved, then it means that there is no feasible solution and the algorithm stops.

Considering that all UEs had already received the minimum amount of RBs, the JRAPA heuristic performs the hughes-hartogs (HH)-based algorithm [9] over each UE j considering a minimum target rate equal to $\overline{r}_j$ and that there is no power limit. If the total amount of power necessary to satisfy all the UEs previously selected is greater than the total power, P^{tot}, available in the BS, the JRAPA algorithm iteratively selects the UE capable of receiving resources with the lowest priority $\overline{r}_j$ and allocate to it the best RB n that was not yet assigned. After that, the HH-based algorithm is reapplied over the RBs of the UE j aiming the minimum rate t_j. If the total amount of power necessary to satisfy the selected UEs did not decrease, the RB n is deallocated from the UE j and it is forbidden to receive any more RBs. If all RBs are assigned and the necessary power is still higher than P^{tot}, it means that no feasible solution is found and the JRAPA algorithm stops. If a feasible solution is found, then the JRAPA algorithm assigns the remaining RBs to the UEs with the best channel quality. Lastly, the remaining power that was not allocated is distributed over all RBs using the HH algorithm, in order to maximize the overall system rate.

B. *Proposed Improvements*

In this section, two improvements are proposed on the JRAPA algorithm in order to improve the result achieved in [5] without increasing its computational complexity. This new version of the JRAPA heuristic is called Improved Joint RB Assignment and Power Allocation (IJRAPA) algorithm. The first improvement is in the calculation of the priority $\overline{r}_j$ of each UE j, presented in (4). There, the priority calculation considers an estimation of the throughput of each UE by mapping its mean SNR over all RBs into rate. However, in usual communication systems, there are a finite number of possible rate values that can be employed by the system given by the number of existing MCSs, as adopted in this paper. In other words, here, the mapping between SNR into rate is done by a surjective increasing function, i.e., there is a continuous range of SNR values that leads to each MCS value. It means that a UEs j_1 with a better channel quality than another UE j_2 and demanding the same minimum rate requirement may have the same priority. Due to this fact, the selection of the UEs that will compete for radio resources following the priority stated in (4) may result into a high outage, as shown in Section IV. Therefore, in order to prioritize UEs with worse channel conditions, instead of using the estimated average throughput, in the improved version of the algorithm proposed by [5], the priority $\overline{r}_j$ is given by the ratio between the average SNR over all RBs and the minimum rate requirement, i.e.,

$$\overline{r}_j = \frac{\frac{1}{N}\sum_{n\in\mathcal{N}}\gamma_{j,n}}{r_j}, \tag{5}$$

for $j \in \mathcal{J}_s$, for all services $s \in \mathcal{S}$. Note that, as the metric changes from a average to another the computational complexity remains the same.

Another issue of the JRAPA heuristic proposed by [5] is that it does not deal with infeasibility, such as the RAISES algorithm. Notwithstanding, differently of the RAISES algorithm, it may lead to non practical solutions, i.e., the algorithm may allocate more power than the total available. In practice, this is a major drawback of the JRAPA algorithm. The second improvement proposed over the state-of-art algorithm is to add the capability of dealing with infeasible instances of the problem. If the algorithm detects that there is no feasible solution, the remaining RBs that were not allocated are assigned to the UEs with better channel conditions. After that, the total available power, P^{tot}, is iteratively distributed to the RBs of each UE j in descending order of priority $\overline{r}_j$ using the HH algorithm, until it meets its minimum rate requirement t_j or there is no more available power to increase the rate of the UE j. If at the end of the power distribution, there is some remaining power, it will be distributed over all UEs using the HH algorithm. Besides of always returning allocation a RB and power allocations that can be employed by the BS, this second improvement also ensures that the maximum number of UEs will be satisfied given the algorithm possibilities. Note that, in the worst-case the IJRAPA will apply the HH algorithm J more times than JRAPA, i.e, both algorithm still dominated by the HH algorithm. Thus, the worst-case computational complexity remains unchanged.

IV. RESULTS

We consider the downlink of one sector deployed in a tri-sectorized cell of a cellular system. The results were obtained by performing several independent snapshots in order to get valid results in a statistical sense. In each snapshot, the UEs are uniformly distributed within the sector, whose BS is placed at its corner. We consider resources arranged in a time-frequency grid with each RB composed of a group of 12 adjacent subcarriers in the frequency dimension and 14

TABLE I
MAIN SIMULATION PARAMETERS.

Parameter	Value	Unit
Cell radius	800	m
Total transmit power	43	dBm
Number of RBs	25	-
Number of MCSs levels	15	-
Path loss	$34.5 + 35 \cdot \log_{10}(d)$	dB
Small-scale fading	IID	-
AWGN power per sub-carrier	-123.24	dBm
Noise figure	9	dB
Shadowing standard deviation	8	dB
Number of snapshots	2000	-

consecutive OFDM symbols in the time dimension, following the specifications in [10].

The propagation model includes a distance-dependent path loss model, a log-normal shadowing component and a Rayleigh-distributed fast fading component. We assume that the link adaptation is performed based on the report of 15 discrete Channel Quality Indicators (CQIs) used by the Long Term Evolution (LTE) system [11]. The SNRs thresholds for MCS switching were obtained by link level simulations from [12]. The main simulation parameters are summarized in Table I.

In Figs. 1 and 2, we depict the results regarding the outage probability and the overall system throughput achieved by the BS. We consider two different scenarios where the BS serves 10 and 15 UEs, respectively. Moreover, all the UEs subscribe the same service, with a throughput requirement equal to 300 kbps, which is the minimum recommendation for a skype video call [13]. The choice of the number of UEs, RBs and services is limited by the computational complexity to obtain the optimal solution, which is $O(\sqrt{2}^{(JNM)})$ [5]. In these simulations, we analyze the impact of varying the minimum number of UEs that must have their requirements met by the BS, k_1. We consider $k_1 = 80$, 90 and 100% of the UEs.

In order to perform a fair comparison between the algorithms, only feasible instances of the problem (3) are considered. As explained in Section III-A, the JRAPA algorithm does not provide a useful solution when it is not capable of meeting the requirement k_1 of minimum number of satisfied UEs, i.e., when an outage event happens. Therefore, the throughput results presented in Fig. 2 consider only instances of the problem where all algorithms yield a feasible solution.

Observe that, in terms of outage probability, the JRAPA algorithm is considerably outperformed by IJRAPA. We can see that the IJRAPA can achieve gains up to 18% in terms of outage compared to JRAPA. On the other hand, regarding the overall system throughput, both JRAPA and IJRAPA reach similar throughput values, however, the later one achieves slightly better values. In fact, for $J = 15$ UEs and $k_1 = 90\% \cdot J$, the IJRAPA achieves a throughput 2.79% higher than the JRAPA.

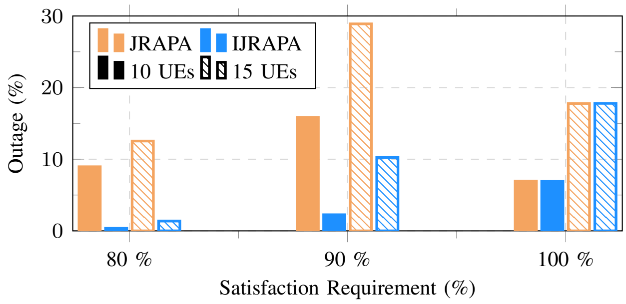

Fig. 1. Outage Probability

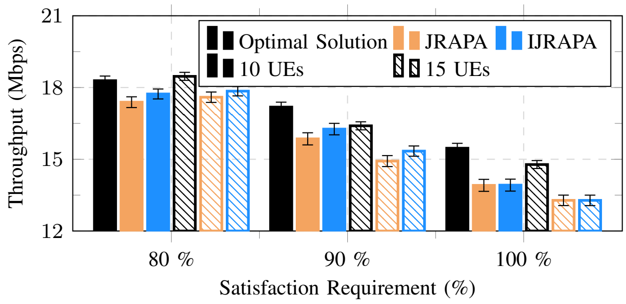

Fig. 2. System Throughput

In order to explain the better performance of the IJRAPA over the state-of-the-art algorithm in Figs. 1 and 2, recall that one of the differences between the JRAPA and the IJRAPA is in the calculation of the UEs' priority. Thus, due to the logarithmic relationship between Signal to Interference-plus-Noise Ratio (SINR) and rate, the amount of power needed to increase the value of MCS used by a RB by one increases exponentially the higher the MCS is. Due to this fact, the UEs with poor channel conditions usually save more power when they receive an additional RB, since rather than using a few RBs employing high MCS values to transmit data, it is preferable to transmit over a larger number of RBs using lower MCS values.

Therefore, in order to save more power, it is preferable that the UEs with poorest channel conditions receive additional RBs first. As already explained in Section III-A, due to the priority adopted by the JRAPA algorithm, a UE with better channel condition may be selected to get additional RBs first before a UE with worse channel conditions. Due to this, the JRAPA may spare more RBs to achieve a transmission power that meets the BS constraint. When the algorithms find a RB and power allocation that meet the power constraint and the UEs' requirements, they assign the rest of the RBs and allocate the remaining power aiming exclusively at maximizing the system throughput. Since the JRAPA algorithm usually needs more RBs to find a feasible solution than the IJRAPA heuristic, it is natural that the overall system throughput achieved by the IJRAPA is higher than the JRAPA one.

When the scenario does not have a feasible solution, an important feature that a QoS constrained RRA algorithm should seek is to provide a good result within the presented circumstances. As already mentioned, the JRAPA algorithm does not deal with infeasibility. In order to further evaluate the performance of the proposed algorithm, the next analyses consider only results where there is no feasible solution available. Here, the proposed algorithm is compared against the "best solution", which is obtained as follows:

1) Try to solve the optimization problem stated in (3);
2) If a feasible solution is found, then the "best solution" is found, otherwise, relax the optimization problem by reducing the number of UEs that should be satisfied by one, i.e., $k_1 = k_1 - 1$, and go back to step 1.

The results presented in Figs. 3 and 4 depict the average satisfaction and the overall system throughput of the proposed algorithm compared to the "best solution" considering only cases that yield infeasible instances of the problem (3). In this scenario, we consider that the BS serves 20 UEs subscribing the same service, with a throughput requirement equal to 500 kbps, which is the minimum recommendation for a high-quality skype video call [13].

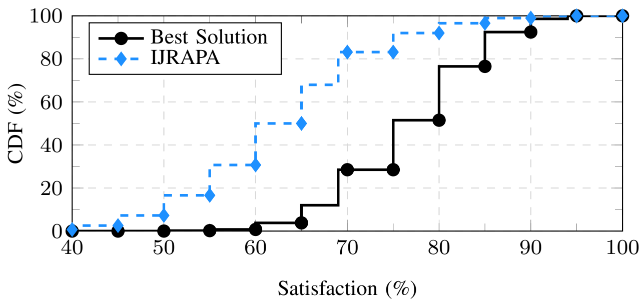

Fig. 3. CDF of the Satisfaction Rate

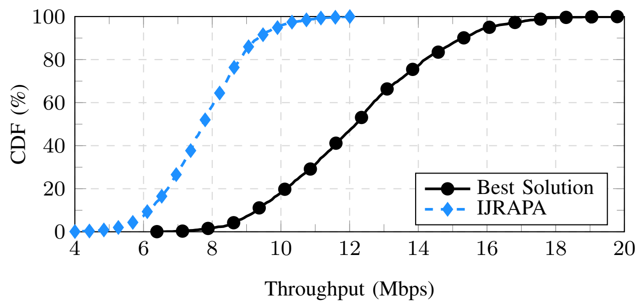

Fig. 4. CDF of the System Throughput

Differently of the JRAPA algorithm, the proposed heuristic is able to provide a practical solution. However, notice that the gap between IJRAPA heuristic and best solution is considerable high. Indeed, the performance loss at the 50$^{\text{th}}$ percentile of the overall system throughput achieved by the IJRAPA algorithm compared to the best solution is 15% and 36.4% in terms of satisfaction and throughput, respectively. Nevertheless, we highlight that the scenario considered in the simulations is very challenging, with a high variance between the UEs' channel quality. In this kind of scenario the radio resource distribution needed to be wisely conducted, which requires a high computational complexity. In this context, we emphasize the trade-off between computational complexity and performance of the proposed solution.

V. Conclusions

In this work, we revisited the problem of jointly allocating power and resources aiming at maximizing the total data rate constrained by meeting the QoS requirements of a minimum number of UEs. We have shown that the heuristic proposed in [5], here referred as JRAPA, has two limitations: 1) depending on the UEs' channel quality, the priorization adopted by JRAPA when the minimum number of UEs that shall be satisfied is less than the total may lead to a high outage rate; and 2) the JRAPA does not deal with infeasible solutions, i.e., in practical scenarios, the JRAPA can not be employed.

In order to overcome these limitations, we proposed in this article a new heuristic, which is an extension of the algorithm described in [5] with the same computational complexity. The simulation results have shown that the proposed algorithm outperforms the JRAPA heuristic, besides providing practical solutions when no feasible solution is found. The performance degradation with respect to the optimal solution observed mainly when infeasible instances of the RRA problem are considered, can be compensated by the low complexity of the proposed algorithm compared with the method employed to obtain the optimal solution.

References

[1] M. Agiwal, A. Roy, and N. Saxena, "Next Generation 5G Wireless Networks: A Comprehensive Survey," *IEEE Commun. Surveys Tuts.*, vol. 18, no. 3, pp. 1617–1655, 2016.

[2] E. Castaneda, A. Silva, A. Gameiro, and M. Kountouris, "An Overview on Resource Allocation Techniques for Multi-User MIMO Systems," *IEEE Commun. Surveys Tuts.*, vol. 19, no. 1, pp. 239–284, 2017.

[3] J. Du, L. Zhao, J. Xin, J.-M. Wu, and J. Zeng, "Using Joint Particle Swarm Optimization and Genetic Algorithm for Resource Allocation in TD-LTE Systems," in *International Conference on Heterogeneous Networking for Quality, Reliability, Security and Robustness (QSHINE)*, Aug. 2015, pp. 171–176.

[4] A. N. Letchford, Q. Ni, and Z. Zhong, "An exact algorithm for a resource allocation problem in mobile wireless communications," *Computational Optimization and Applications*, vol. 68, no. 2, pp. 193–208, Nov. 2017.

[5] W. V. F. Maurício, F. R. M. Lima, T. F. Maciel, and F. R. P. Cavalcanti, "Joint resource block assignment and power allocation problem for rate maximization with QoS guarantees in multiservice wireless systems," *J. Comm. and Inf. Syst.*, vol. 31, no. 1, 2016.

[6] F. R. M. Lima, T. F. Maciel, W. C. Freitas, and F. R. P. Cavalcanti, "Resource Assignment for Rate Maximization with QoS Guarantees in Multiservice Wireless Systems," *IEEE Trans. Veh. Technol.*, vol. 61, no. 3, pp. 1318–1332, Mar. 2012.

[7] C. Seol and K. Cheun, "A Statistical Inter-Cell Interference Model for Downlink Cellular OFDMA Networks under Log-Normal Shadowing and Multipath Rayleigh Fading," *IEEE Trans. Commun.*, vol. 57, pp. 3069–3077, Oct. 2009.

[8] F. R. M. Lima, S. Wänstedt, F. R. P. Cavalcanti, and W. C. Freitas, "Scheduling for Improving System Capacity in Multiservice 3GPP LTE," *J. of Electrical and Computer Engineering*, no. 819729, 2010.

[9] D. Hughes-Hartogs, "Ensemble Modem Structure for Imperfect Transmission Media," US Patent 4 833 706, May, 1989.

[10] 3GPP, "Physical layer aspect for evolved Universal Terrestrial Radio Access (UTRA)," 3rd Generation Partnership Project (3GPP), TR 25.814, Oct. 2006. [Online]. Available: http://www.3gpp.org/ftp/Specs/html-info/25814.htm

[11] ——, "Evolved Universal Terrestrial Radio Access (E-UTRA); Physical layer procedures," 3rd Generation Partnership Project (3GPP), TS 36.213, Oct. 2010. [Online]. Available: http://www.3gpp.org/ftp/Specs/html-info/36213.htm

[12] C. Mehlführer, M. Wrulich, J. C. Ikuno, D. Bosanska, and M. Rupp, "Simulating the Long Term Evolution Physical Layer," in *Proc. of the European Signal Processing Conf.*, Glasgow, Scotland, Aug. 2009.

[13] Microsoft. How much bandwidth does skype need? [Online]. Available: https://support.skype.com/en/faq/FA1417/how-much-bandwidth-does-skype-need