RADIO RESOURCE SCHEDULING ALGORITHMS FOR COOPERATIVE CELLULAR NETWORKS WITH SHADOWING EFFECTS

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ABSTRACT

This paper investigates radio resource scheduling for a cooperative cellular network. A method based on exhaustive search is used to get the optimal solution. According to the results from the optimal solution, two power based algorithms which aim to maximize the total network bandwidth efficiency and to reduce the complexity are then proposed. The results from the proposed algorithms show that they can achieve 93.03% and 97.21% of the optimal total bandwidth efficiency respectively whilst also reducing the complexity significantly. In addition, one of the proposed algorithms also exhibits a superior performance in a non-shadowing setting, achieving over 99% of the optimum total bandwidth efficiency.

I. INTRODUCTION

With the rapid development of the mobile electronic device market and the high demands of the device users, wireless communication systems are subject to increasing date rate, spectrum efficiency and Quality of Service (QoS) requirements. With limited available spectrum, efficient use of resources to get a high QoS for the users is a key problem. Resource allocation problems of both single cell environments and multi-cell environments have been investigated with regard to several aspects such as user scheduling, power allocation, fairness and joint scheduling and power allocation [1]-[12]. However, most of the previous research focused on power and channel allocation, resource block scheduling was not well-studied [5][8][10][12]. Moreover, somewhat surprisingly the optimal solution of resource block scheduling to maximize the total network bandwidth efficiency including cooperative transmission in cellular networks has seldom been addressed. This paper investigates the use of resource blocks to get as much total network bandwidth efficiency as possible including the possibility of cooperative transmission between cells. There are several earlier works on the optimal solution of joint resource scheduling and power control [1][2][6]. Although some algorithms have been published on various specific settings such as a symmetric network of interfering links and a 2-cell network, the general optimal solution is considered to be very complex to solve especially when the number of cells and the number of users increase due to the SINR expression remaining nonconvex [1][2][6][12]. In this paper, a method based on exhaustive search is used to get the optimal solution for a general network. Moreover, two power-based sub-optimal algorithms aiming to maximize the total network bandwidth efficiency whilst reducing complexity are proposed.

The remainder of this paper is organized as follows: the investigated network and related mathematics are presented in section II. The optimal solution and the proposed algorithms are explained in section III and IV. Simulation results of the optimal solution and the proposed algorithms are discussed in section V. Section VI concludes this paper.

II. SYSTEM MODEL

II.1 Network layout and setting

The investigated network consists of N adjacent cells with one Base Station (BS) located at the center of each cell. In total of U users are randomly placed within these N cells and M orthogonal resource blocks in total are available for scheduling in this network. Frequency reuse is flexible and any one resource block may be scheduled in any of the N cells. Data may be transmitted cooperatively from multiple base stations to one user on one resource block (cooperative transmission) or independent data may be transmitted from multiple base stations to multiple users on a non-cooperative basis (multiple access). A resource block is assumed to be the smallest resource unit that can be scheduled and the power of each resource block is assumed to be the same.

The distance-dependent path loss and the simulation parameters listed in table 1 are for a typical urban macro environment in LTE defined by 3GPP [14].

II.2 Problem statement

The objective formula is obtained based on the scheduling matrix in table 2. In an N cell layout, M

Table 1: Simulation parameters

Parameter	Value
Network layout	Hexagonal 3 cells
Cell radius	500m
Antenna	Omnidirectional
Carrier Frequency	2GHz
Bandwidth	10MHz
Log-normal shadowing standard deviation	10dB
Distance-dependent path loss	$128.1+37.6*\log_{10}(d)$ d in km
Thermal noise power spectral density	-174dBm/Hz
Maximum BS transmit power	40watts
Mobile station noise figure	9dB
Minimum distance between user and BS	35m

Table 2: Matrix of scheduling M resource blocks (RB) among N base stations (BS) and U users

BS \ RB	M	……	2	1
N	u_{NM}	…….	u_{N2}	u_{N1}
. .	. .	u_{nm}	. .	. .
2	u_{2M}	…….	u_{22}	u_{21}
1	u_{1M}	……	u_{12}	u_{11}

resource blocks will be scheduled for the transmission of signals from N base stations to U users (downlink transmission). The value of u_{nm} is the index of which user receives a signal and its range is from 0 to U: 0 means no user, 1 means $user_1$, etc. u_{nm} is used to represent the case that resource block m is scheduled for the transmission from the n^{th} base station to the user u_{nm}, e.g., if u_{12} is 3, u_{12} indicates that resource block 2 is scheduled for the transmission from the 1^{st} base station to $user_3$. The values of u_{nm} in the matrix vary with different combinations of scheduled resource blocks. The number of all combinations for this network layout is $(U+1)^{NM}$. For the exhaustive search, all the possible combinations are considered [13].

The key equation relating to the scheduling matrix is the expression of SINR of any user u receiving a signal on any resource block m (the m^{th} column), which is

$$S'_{m,u} = \frac{\sum_{n=1}^{N}(k_{nmu}P_{n,u})}{N_s + \sum_{n=1}^{N}(k_{nmv}P_{n,u})}, \quad (1.1)$$

with respect to the following conditions:

$$\begin{cases} k_{nmu} = 0 \text{ and } k_{nmv} = 0, & \text{if } u_{nm} = 0; \\ k_{nmu} = 1 \text{ and } k_{nmv} = 0, & \text{if } u_{nm} = u; \\ k_{nmu} = 0 \text{ and } k_{nmv} = 1, & \text{if } u_{nm} \neq u \text{ and } u_{nm} \neq 0. \end{cases} \quad (1.2)$$

In (1.1), $P_{n,u}=P_m/[P_L(d_{n,u})*P_{shad}]$ (P_m is transmit power per resource block m; P_L is path loss, $d_{n,u}$ is the distance from BS_n to $user_u$; P_{shad} represents the shadowing effect) denotes the received power of $user_u$ from the n^{th} base station. N_s represents the noise power. k_{nmu} and k_{nmv} are binary indices for allocating $P_{n,u}$ to be signal or interference according to the value of u_{nm} in the matrix of table 2.

Total bandwidth efficiencies can be calculated according to different scheduling combinations in the scheduling matrix and the case in the scheduling matrix corresponding to the maximal total bandwidth efficiency is the optimal solution for this resource block scheduling problem. The objective formula is:

$$\arg\max_{u_{nm}} \frac{1}{B_{total}} \sum_{m=1}^{M}\sum_{u=1}^{U} B_m \log_2\left(1+\frac{\sum_{n=1}^{N}(k_{nmu}P_{n,u})}{N_s+\sum_{n=1}^{N}(k_{nmv}P_{n,u})}\right), \quad (2)$$

where B_m denotes the bandwidth per resource block m. B_{total} is the total bandwidth used for the scheduling.

III. OPTIMAL RESULTS

III.1 Optimal cases

For the simulation of the optimal solution in this paper, a 3-cell layout with one base station in the center of each cell and one user per cell is used. The number of available resource blocks is three. 1,000,000 independent user drops (3 users per drop) in this network are generated to obtain all of the optimal cases. According to table 2, the case is expressed as 9 digits: $u_{33}u_{32}u_{31}u_{23}u_{22}u_{21}u_{13}u_{12}u_{11}$. Thus, there are 4^9 possible combinations for getting the optimal solution in the investigated network. However, analysis of the optimal results reveals that only 45 of these possible combinations are candidates for optimum allocation. These 45 candidates of optimal cases can be further categorized into 4 types: full cooperation case, 2/3 reuse non-cooperative case, full frequency reuse non-cooperative case and the handover cases for the above three types. The full cooperation case means that all the base stations in the network use all the resource blocks to transmit a signal to the same user. The 2/3 reuse non-cooperative case means that one of the base stations in the network is not transmitting on the resource blocks in order to reduce interference to users in the other two cells. The full frequency reuse non-cooperative case means that all the users in the network are served by a base station using all the resource blocks and also they get interference from all the other base stations in the network.

III.2 User distributions for inspiring the sub-optimal algorithms

In the 1,000,000 user drops, 83.46% choose one of the cases from full cooperation case, 2/3 reuse non-cooperative case and full frequency reuse non-cooperative case as the optimal case. Furthermore, 14.65% choose the full frequency reuse non-cooperative case which is selected by the most user drops. This is the reason that this case is set as the default case in the proposed algorithm 2 and also it is a special case of Round-robin scheduling. The handover cases appear due to shadowing effects, and all of them are handover versions of the dominant three types of the optimal cases and rarely happen. From the observation of the user distributions for all the optimal cases, the users with the resources from the base station of an adjacent cell are mainly located in the area close to that adjacent cell; the users with the resources from their own base station are mainly located around their own base station and far away from the other two adjacent cells; the users with the resources from both their own base station and the base station of an adjacent cell are mainly located far away from the third cell which is not transmitting to the users; All these results imply that the resources are scheduled for the transmission from a base station to the user who has a good channel condition.

IV. PROPOSED ALGORITHMS

Although the exhaustive search guarantees the optimal solution, it is highly computationally demanding [4][13]. Two power based algorithms are proposed to maximize the total network bandwidth efficiency and to reduce the complexity compared with the exhaustive search. These two proposed algorithms can be implemented in a general network of N cells with U users in total (at least one user in each cell) and M resource blocks in total. In order to maximize the total bandwidth efficiency, it is highly possible that the user with the best channel condition in each cell gets all the resource blocks (Greedy scheduling). Thus, the first step for both algorithms is to select the user with the highest SINR value for each cell as the candidates for the scheduling process. In the SINR value, the received power from the user's own base station is the signal and the received powers from the other base stations are the interference. Thus, there are N users in total selected for the scheduling process.

IV.1 Algorithm 1

The first proposed algorithm is designed to use received powers and bandwidth efficiencies to allocate the resources. It uses received powers from each base station to each user candidate to allocate most of the resource blocks to several users, and then the bandwidth efficiency values are computed and compared in order to finalize the scheduling of all the resources. The algorithm 1 works as the following steps where pr stands for received power and pr_{jk} denotes the pr value from $user_j$ to BS_k:

1. Calculate pr values from each base station to each user and select the largest pr value for each base station to a corresponding user, e.g., for a 3-cell network, pr_{11}, pr_{32} and pr_{23} are the three largest pr values for BS_1, BS_2 and BS_3.
2. Delete the smallest pr value from the N largest pr values selected in 1, e.g., if $pr_{11}<pr_{32}<pr_{23}$, delete pr_{11}.
3. The N-1 users corresponding to the remaining N-1 pr values from the N-1 base stations are selected as N-1 scheduled users, e.g., $user_3$ gets resources from BS_2 and $user_2$ gets resources from BS_3. So far, the scheduling case is that the N-1 users get all the resource blocks from their corresponding N-1 base stations according to the remaining N-1 pr values.
4. Resources from the base station corresponding to the deleted pr value in 2 are going to be scheduled to either of the N users in the layout or they are not scheduled, e.g., pr_{11} is deleted, so the resources from BS_1 can be allocated to no user or any user in the network. Calculate N+1 total bandwidth efficiency values corresponding to these N+1 cases, and the case with the highest total bandwidth efficiency value is selected as the final resource block scheduling case.

IV.2 Algorithm 2

The second proposed algorithm is designed to distribute the scheduling of the resource blocks to any of the four optimal types according to the users' channel conditions. There could be more than four optimal types when N>3, however this investigation is out of this paper and could be put into the future work. The 2/3 reuse non-cooperative case is extended to (N-1)/N reuse non-cooperative case. The proposed algorithm uses received powers and SINR values to assign resources. The algorithm 2 works as the following steps where The SINR value for a scheduling case is the multiplication of the SINR values of the users in the scheduling case:

1. For Full cooperation case

i. The SINR value of full cooperation transmission to a user u is the largest in those of full cooperation transmission to any of the N users in the layout.

ii. The SINR value of full cooperation transmission to a user u is the largest in those of the cases when the user u gets all the resource blocks from its own base station while the resource blocks from the other N-1 base stations can be scheduled to any of the N users in the layout.

If both 1-i and 1-ii are satisfied, the user u gets all the resource blocks from all the base stations in the layout, e.g., if $user_1$, $user_2$ and $user_3$ are the users for the scheduling process in a 3-cell layout, $user_1$ is the user u, then $user_1$ gets all the resource blocks from BS_1, BS_2 and BS_3.

2. For (N-1)/N reuse non-cooperative case

i. The SINR value of the case that the corresponding base station of a user u is not transmitting while the other N-1 base stations schedule all the resource blocks to their own users is the largest in those of the same situation for any of the N users in the layout.

ii. The SINR value of the case that the corresponding base station of a user u is not transmitting while the other N-1 base stations schedule all the resource blocks to their own users is the largest in those of the cases when the corresponding base station of the user u schedules all the resource blocks to any of the N users in the layout or does not transmit while the other N-1 base stations still schedule all the resource blocks to their own users.

If both 2-i and 2-ii are satisfied, the corresponding base station of the user u is not transmitting while the other N-1 base stations schedule all the resource blocks to their own users, e.g., BS_1 is not transmitting ($user_1$ gets no resource) while BS_2 and BS_3 schedule all the resource blocks to $user_2$ and $user_3$ respectively.

3. For Handover case and non-cooperative case

i. When the optimal handover cases are known (in the simulation network layout in this paper), the pr values from each base station to each user are computed and the user with the highest pr value for each base station gets all the resource blocks from that base station if the resultant scheduling case belongs to one of the known handover cases; otherwise, the scheduling case goes to full frequency reuse non-cooperative case, e.g., if $user_1$ has the highest pr value for BS_2, $user_2$ has the highest pr value for BS_1 and $user_3$ has the highest pr value for BS_3, $user_1$ gets all the resources from BS_2, $user_2$ gets all the resources from BS_1 and $user_3$ gets all the resources from BS_3 if this scheduling case is one of the known handover cases; otherwise, $user_1$ gets all the resources from BS_1, $user_2$ gets all the resources from BS_2 and $user_3$ gets all the resources from BS_3.

ii. When the handover cases are unknown (in a general network), the user with the highest pr value for each base station gets all the resource blocks from that base station.

V. Simulation Results

In the investigated network, there is one user located in each of the adjacent three cells, and in total of three resource blocks are scheduled according to optimal solution (based on the exhaustive search), non-cooperation transmission (a special case of Round-robin scheduling) and proposed algorithms. Results are obtained for an ensemble of 1,000,000 independent user drops (3 users per drop).

V.1 Algorithm results

The CDF of total network bandwidth efficiencies achieved by the proposed algorithms are compared with those of the optimum allocation and non-cooperation in figure 1, figure 2-a and figure 2-b. figure 1 and figure 2 show results for the algorithms 1 and 2 respectively whilst figure 2-a considers the shadowing environment and figure 2-b considers the non-shadowing environment. The accuracy measurements of the proposed algorithms are presented in the tables below their corresponding figures. 'Case accuracy' evaluates the percentage of user location cases where the algorithm replicates the optimum allocation. 'Bandwidth efficiency' evaluates the fraction of the optimum bandwidth efficiency that the algorithm achieves, averaged across the ensemble of user locations.

In figure 1, the non-cooperation case performs much worse than the proposed algorithm 1, and the two curves of the optimum and algorithm 1 become closer to

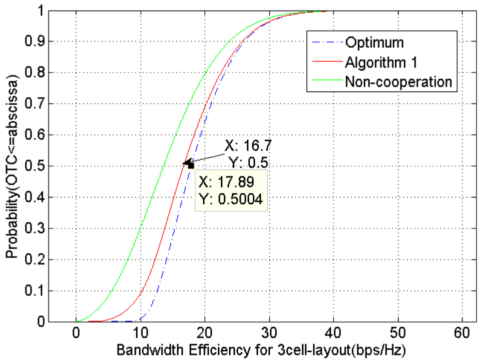

Figure 1: Comparison of the network bandwidth efficiency for algorithm 1 (shadowing)

Table 3: Algorithm 1 accuracy

Case accuracy (%)	Bandwidth efficiency (%)
54.70	93.03

each other when the value of bandwidth efficiency increases, and the difference between the two curves at the middle point (0.5) is about 1 bps/Hz. This indicates that the performance of the proposed algorithm is quite good on average but underperforms the optimal solution slightly at lower efficiencies (lower SINRs).

From table 3, it can be seen that although just over half of the optimal cases can be selected correctly, the bandwidth efficiency accuracy of the algorithm 1 is over 93%. This suggests that even when a sub-optimal case is selected only a small amount of bandwidth efficiency is lost and hence the sub-optimum allocations obtained are near optimal in most cases.

From figure 2-a, the two curves of the optimum and the algorithm 2 are nearly the same from 7bps/Hz to 9bps/Hz and above 23bps/Hz while also close to each other from 9bps/Hz to 23bps/Hz. This shows that this proposed algorithm 2 performs well especially when the channel condition is very bad.

Figure 2-b shows that the curve of algorithm 2 is very close to the optimum curve whilst far away from the non-cooperation case, which indicates that this proposed algorithm 2 also has great performance in a non-shadowing environment.

From table 4, 76.16% of optimal cases can be correctly selected by the algorithm 2 and 97.21% of the total network bandwidth efficiency of optimum is achieved when shadowing is included. Moreover, this algorithm can correctly select over 85% of optimal cases and over 99% of the optimal total network bandwidth efficiency is achieved in a non-shadowing environment. These prove that the algorithm 2 can give a good performance in both non-shadowing and shadowing environments.

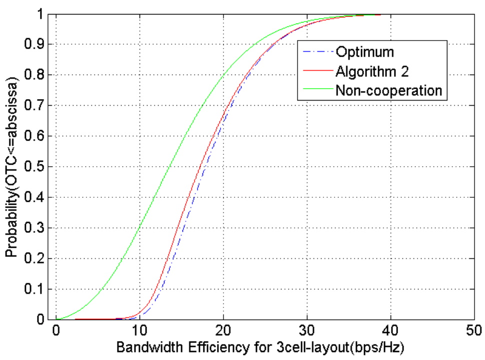

Figure 2-a: Comparison of the network bandwidth efficiency for algorithm 2 (shadowing)

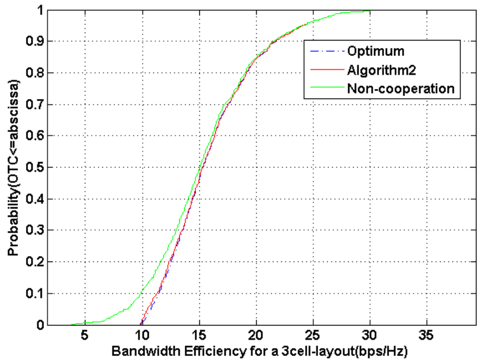

Figure 2-b: Comparison of the network bandwidth efficiency for algorithm 2 (non-shadowing)

Table 4: Algorithm 2 accuracy

Shadowing effect	Case accuracy (%)	Bandwidth efficiency (%)
Shadowing	76.16	97.21
Non-shadowing	87.40	99.64

V.2 Algorithm complexity

Table 5 lists the complexity equations of the optimal solution and the two proposed algorithms based on the N-cell layout with U users and M resource blocks. For the simulated case, the complexity of the exhaustive search is $O(4^9\rho_{com} + (4^9 - 1)n)$, the complexity of the algorithm 1 is $O(3n^2 + 17n + 4\rho_{com})$ and the complexity of the algorithm 2 is $O(76n^2 + 243n + 252 + \rho_{com})$, where ρ_{com} is the complexity of calculating the total network bandwidth efficiency. Obtaining the optimal solution requires calculating the total bandwidth efficiency 4^9 times while the proposed algorithms only need to do this 4 times or once. Hence, the computational effort is reduced by the proposed algorithms.

Figure 3 shows the logarithmic complexity surface of getting the optimal solution in a 3-cell network

Table 5: Complexity equations

Algorithm	Complexity equation
Optimum	$(U+1)^{NM}\rho_{com} + [(U+1)^{NM} - 1]n$
Algorithm 1	$Un^2 + (N^2 + UN - 1)n + (N+1)\rho_{com}$
Algorithm 2	$N^{N-1}[(2N-1)n^2 + (2N^2 - N + 1)n + 2N^2] + (4N^2 - 3N + U + 1)n^2 + (4N^3 - 2N^2 + UN + N - 3)n + 4N^3 - 2N^2 + \rho_{com}$

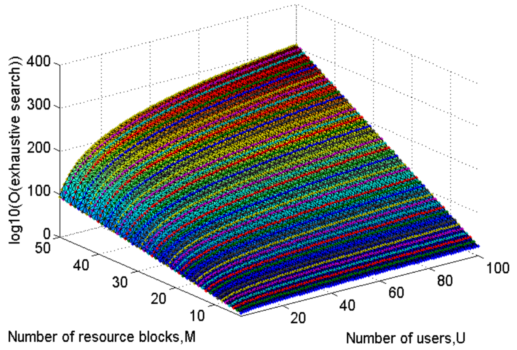

Figure 3: Complexity surface of getting the optimal solution (U, M) with N=3

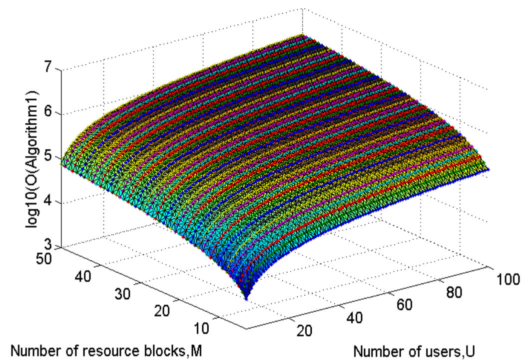

Figure 4: Complexity surface of the proposed algorithm 1 (U, M) with N=3

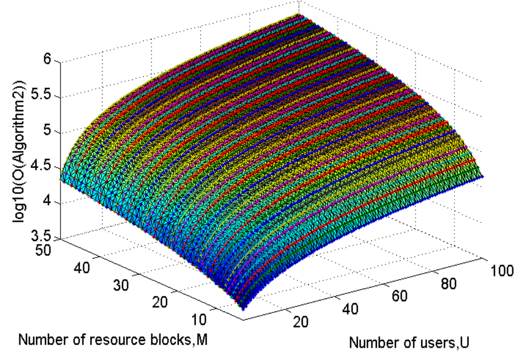

Figure 5: Complexity surface of the proposed algorithm 2 (U, M) with N=3

varying with the values of U (from 3 to 100) and M (from 3 to 50). When U is fixed at a value, the logarithmic complexity increases linearly with the increasing of M; when M is fixed at a value, the logarithmic complexity increases logarithmically with the increasing of U. The range of the logarithmic complexity values is from 8 to 306.

Figure 4 and figure 5 are the logarithmic complexity surface of the proposed algorithms in a 3-cell network. From both figures, the complexity surface rises up and inclines to be flat when either M or U increases. Compared with figure 3, the range of the complexity values is significantly reduced in both figures, which is only from 3 to 7. Therefore, the complexity of either of these two proposed algorithms is much lower than that of getting the optimal solution.

VI. CONCLUSION

In this paper, radio resource scheduling for a cellular network with shadowing effects has been investigated. The general optimal solution was obtained by a method based on the exhaustive search. This method was then implemented in a 3-cell network and the results showed that there are four types of transmissions in the optimal solution. Based on the resulting optimal cases, two low-complex algorithms aiming to maximize the total bandwidth efficiency were proposed. The simulation results showed that these two algorithms can achieve 93.03% and 97.21% of the total bandwidth efficiency of optimum respectively, and both of them can significantly reduce the complexity of getting the optimal solution. Moreover, algorithm 2 can achieve over 99% of the optimum total bandwidth efficiency in a non-shadowing environment. For the proposed sub-optimal algorithms, user fairness could be considered in the future such as by using proportional fair or max-min scheduling, and methods to reduce the quantity of SINR information required by the algorithms are also of interest. Further investigation could be done in a network of more than 3 cells.

REFERENCES

[1] D. Gesbert, S. G. Kiani, A. Gjendemsio, G. E. Ien, "Adaptation, coordination, and distributed resource allocation in interference-limited wireless networks", *IEEE ISWCS*, Vol. 95, Issue. 12, pp. 2393-2409, Oct. 2007.

[2] D. Gesbert, S. Hanly, H. Huang, S. Shamai Shitz, O. Simeone, W. Yu, "Multi-cell MIMO cooperative networks: a new look at interference", *IEEE Journal on Selected Areas in Communications*, Vol. 38, Issue. 9, pp. 1380-1408, Nov. 2010.

[3] M. Fathi, "Price-based spectrum sharing and rate allocation in the downlink of multihop multicarrier wireless networks", *IET Networks,* Vol. 3, Issue: 4, pp. 252-258, Nov. 2014.

[4] T. Issariyakul, E. Hossain, "Optimal radio channel allocation for fair queuing in wireless data networks",

IEEE International Conference on Communications (ICC, Vol. 1, pp. 142-146, May 2003.

[5] Ya-Feng Liu, Yu-Hong Dai, "On the complexity of joint subcarrier and power allocation for multi-user OFDMA systems", *IEEE* transactions on Signal Processing, Vol. 62, Issue: 3, pp. 583-596, Jan. 2014.

[6] S. R. Bhaskaran, S. V. Hanly, N. Badruddin, J. S. Evans, "Maximizing the sum rate in symmetric networks of interfering links", *IEEE Transactions on Information Theory*, Vol. 56, Issue. 9, pp. 4471-4487, Sep. 2010.

[7] I. Hou, C. S. Chen, "Self-organized resource allocation in LTE systems with weighted proportional fairness", *IEEE international Conference on Communications (ICC'12)*, pp. 5348-5353, Jun. 2012.

[8] G. Bansal, M .J. Hossain, V. K. Bhargava, Tho Le-Ngoc, "Subcarrier and power allocation for OFDMA-based cognitive radio systems with joint overlay and underlay spectrum access mechanism", *IEEE Transactions on Vehicular Technology*, Vol. 62, Issue: 3, pp. 1111-1122, Mar. 2013.

[9] Tianhang Fu, Shaoyi Xu, Kyung Sup Kwak, "Geometric programming based resource allocation for mobile relays on vehicles", 2014 *IEEE 79th conference on Vehicular Technology Conference (VTC Spring)*, pp. 1-5, May 2014.

[10] G. G. Sedhom, M. Abd-Elnaby, N. W. Messiha, "Efficient subcarrier-power allocation scheme for multiuser OFDM systems", *2014 International Conference on Engineering and Technology(ICET)*, pp. 1-8, Apr. 2014.

[11] Zhanyang Ren, Shanzhi Chen, Bo Hu, Weiguo Ma, "Energy-efficient resource allocation in downlink OFDM wireless systems with proportional rate constraints", *IEEE Transactions on Vehicular Technology*, Vol. 63, Issue: 5, pp. 2139-2150, Jun. 2014.

[12] A. Gjendemsjoe, D. Gesbert, G. Oien, and S. Kiani, "Binary power control for sum rate maximization over multiple interfering links", *IEEE Trans. Wireless Commun.*, Vol. 7, No. 8, pp. 3164-3173, Aug. 2008.

[13] H. W. Khun, "The Hungarian method for the assignment problem", *Naval Research Logistics Quarterly*, Q.2, pp. 83-97, 1995. http://tom.host.cs.st-andrews.ac.uk/CS3052-CC/Practicals/Kuhn.pdf

[14] *LTE; Evolved universal terrestrial radio access (E-UTRA); Radio frequency (RF) requirements for LTE Pico Node B (Release 9)*, 3GPP TR 36.931, May 2011.