Dynamic and Load-Adapting Distributed Fractional Frequency Reuse Algorithm for Ultra-Dense Networks

Sonia Giménez*, Daniel Calabuig, José F. Monserrat and Narcís Cardona

Universitat Politècnica de València, Instituto de Telecomunicaciones y Aplicaciones Multimedia,
Camino de Vera s/n - 8G Building - Access D - 46022 Valencia (Spain)
*Corresponding author: sogico@iteam.upv.es

Abstract

Mobile networks today and in the near future tend to increase the density of access points, creating a heterogeneous structure of cells with overlapping coverage. The management of this situation of massive interference has been addressed to date in a static, centralized manner, which cannot scale to the ultra-density levels for the 5G. This paper proposes an alternative for this issue, where a dynamic and load-adapting distributed fractional frequency reuse technique is proposed. Still being feasible and simple to implement, this algorithm achieves a significant improvement in the power consumption while boosting up to 60 times the cell-edge user throughput. Furthermore, results prove that the proposed scheme improves the fairness between the users, presenting a good compromise between cell-centre user average rate reduction and cell-edge rate increase. The algorithm is able to adapt to the different load conditions, allocating users to the most appropriate band depending on the distribution of interference. Finally, our proposal implies a minor increase in signalling among nodes, being current solutions based on X2 interface valid for its information needs.

Keywords: ultra-dense networks, fractional frequency reuse, small cells, power consumption, interference management.

1. Introduction

The deployment of small cells in outdoor scenarios has been shown as an efficient tool to improve cell coverage as well as to increase user-experienced throughput, especially for cell-edge users. In these heterogeneous networks (HetNets), low power nodes are deployed in those areas with an increased demand of traffic or poor coverage. Nevertheless, the inclusion of small cells within the macro-cell coverage area leads to an increase of inter-cell interference. Three main mechanisms are employed in HetNets to enable the network operation: interference management, cell range expansion and interference cancellation [1].

Fractional frequency reuse (FFR) schemes can be applied as an interference management technique. In FFR schemes, the whole available bandwidth is divided into several sub-bands. Every cell is split into two areas, cell-centre and cell-edge, which are forced to use different sub-bands. Sub-bands are allocated among the cells in such a way that contiguous cells do not use the same sub-band in the cell-edge region. In order to achieve higher spectral efficiencies, optimum size of cell-centre and cell-edge regions as well as the number of sub-bands in which the total frequency band is divided must be selected [2]. It has been shown that these optimal values are topology dependent [3], and thus static planning of a FFR scheme designed for a specific network topology cannot be applied to a different network topology. Moreover, FFR schemes for future networks have to be more flexible and possess the ability to respond to not only traffic load variations but also deployment modifications [4].

On the other hand, as the density of network nodes is expected to increase significantly in the following years, a centralized adjustment of the FFR scheme will become impractical and unfeasible. Distributed solutions have been shown to achieve inferior performance when compared to centralized solution. However, distributed solutions have the benefit of easier implementation and better scalability [5]. For that reason, a distributed and dynamic clustering algorithm must be applied to the network in order to face the design of FFR schemes for ultra-dense networks. Optimum distributed clustering solutions required complex optimizations to be solved through the exchange of a big amount of messages among the nodes of the network, what might congest the already-limited backhaul network [5].

Distributed FFR schemes are interference coordination solutions with good scalability and easy implementability features, suitable for the future ultra dense networks.

In this work, we propose a dynamic and load-adapting distributed fractional frequency reuse (DLAD-FFR) scheme that is able to improve significantly the cell-edge experienced users' rate while reducing the power consumption of the network. Furthermore, this scheme is simple to implement and does not imply the exchange of a big amount of information among nodes, what benefits the application in saturated backhaul networks. Results through simulation corroborate the good behaviour of the proposed algorithm, which pave the way for a next generation of FFR algorithms better suited to the demands of the coming 5G.

2. Classic interference coordination in OFDMA systems

One of the most limiting aspects of the system performance in OFDMA-based cellular systems like LTE is the inter-cell interference, especially for users in the cell edge. This section briefly describes some classic mechanisms for interference mitigation in these systems.

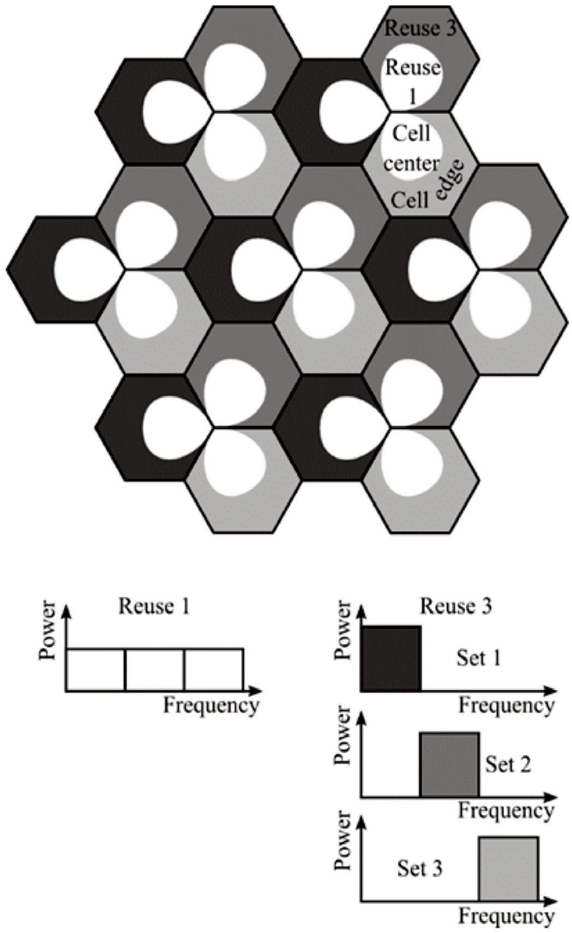
2.1. Orthogonal Resource Allocation

In LTE the basic resource element is the Radio Block (RB) consisting of 12 subcarriers with 15 kHz spacing allocated during one subframe of 1ms. In Orthogonal Resource Allocation (ORA) the set of available RBs is divided into non overlapped sets, following a Frequency Division Multiple Access (FDMA) philosophy. As in legacy GSM systems, the frequency reuse factor,1/k, is the rate at which the same frequency can be used in the network. In order to reduce interference, contiguous cells do not use the same set of RBs. The RB distribution can be decided in different ways. Localized ORA refers to the case in which each set comprises consecutive RB, whereas in Distributed ORA each set of RBs is spanned over the whole bandwidth.

As proposed in some works, this ORA might be changed dynamically according to the user channel state and interference distribution [6]. However, the required huge amount of information to be exchanged in the system makes this kind of dynamic mechanisms to be far away from being implemented in next generation mobile networks.

2.2. Static Inter-Cell Interference Coordination

OFDMA systems were designed to support frequency reuse of one, that is, all cells operating on the same frequency. In order to reduce the cell edge interference problem, the FFR method proposes an appropriate configuration of the RB usage. In Soft FFR, users are classified into cell-centre or cell-edge depending on their location. The base stations are allowed to use all the RBs in their proximities and hence for the cell-centre users but with reduced power. In the cell edge, the RBs are distributed into the base stations using a reuse factor of 3 [7]. Thus,



■ **Figure 1.** Interference Coordination with Fractional Frequency Reuse.

the RBs are divided into 3 sets and each base station is responsible for the management of one of those sets. With this configuration, the full frequency reuse one is preserved for cell-centre users hence maximizing spectral efficiency, whereas ORA is implemented for cell-edge users to mitigate the interference. Figure 1 depicts this scenario with seven sites.

2.3. Semi-dynamic Inter-Cell Interference Coordination

FFR described above represents a static interference coordination method associated with cell planning. Reconfigurations are exceptional and signalling among base stations is not needed at all. However, this kind of strategy may impose some limitations to the system performance since variations in cell load and user distribution are not considered. Semi-dynamic Inter-Cell Interference Coordination (ICIC) applies to interference coordination in which some communication among neighbouring cells is established in order to coordinate the scheduling. The reuse planning and frequency sharing is dynamically optimized across cells according to the network load and interference situation on a frame-by-frame basis. Therefore, all the cells can operate on the same frequency channels depending on the specific usage of the reserved bands.

3. Dynamic and Load-Adapting Distributed FFR algorithm (DLAD-FFR)

In FFR schemes, frequency reuse factor applied in cell-edge region must tend towards a reuse factor of 1 when the network is noise-limited, case in which it is more efficient that all the cells use the whole available bandwidth. However, frequency reuse factor applied may be increased when interference over noise ratio (INR) increases, leading to an interference-limited network. For that reason, in order to achieve the maximum spectral efficiency, not only cell-centre and cell-edge region definition must be flexible in a FFR scheme, but also the number of sub-bands allocated to each of the regions as well as the specific sub-bands allocated at every cell.

In the proposed technique, cell layout is divided into an overlapping set of clusters. Coordination messages are exchanged only among the cells within the same cluster, which allows the application of a fractional reuse of resources in a distributed fashion. Once the set of clusters is defined, using a simple protocol of exchange of messages among the M cells within a cluster, every cell configures its best set of resources to be used by the cell-edge users, called preferential resources.

The way in which a cell configures its preferential resources consists in interrogating the neighbours within the same cluster about which resources they are using as preferential. Then, the cell selects as preferential sub-bands some of the free sub-bands not already used as preferential in any of the neighbours. Contrarily, the same set of fixed sub-bands is used for the cell-centre users in every cell of the network. An appropriate relation between the number of cells per cluster and the width of the sub-bands must be set in order to guarantee the existence of a free band for each cell. An example of this per-cluster sub-band definition is depicted in Figure 2.

It is worth to highlight that cell-centre users are allowed to use the preferential band assigned to its own cell whenever any user is classified as cell-edge user in the cell. Moreover, cell-centre users are allowed to use also the rest of frequency bands, defined as preferential bands in the neighbour cells within the same cluster, as long as these bands are not allocated to cell-edge users on those cells. This feature provides the scheme the flexibility to tend to reuse 1 when beneficial.

Thanks to the Dynamic and Load-Adapting FFR algorithm, not only interference is reduced but also the power consumption of the network.

The novel feature in this scheme is the cell-edge and cell-centre definition. User classification as cell-edge or cell-centre user does not depend on its location. However, user classification is calculated to optimize the total throughput of the cell that serves the user. To this aim, a statistical study on user expected throughput when it is classified as cell-edge or cell-centre user is conducted for every user. On the one hand, to classify a user as cell-edge user implies that this user will be allocated to the cell-edge sub-bands and that these sub-bands will be blocked in the rest of cells within the same cluster. Therefore, cell-edge user will experience a better SINR but the number of available resources that it will be able to use will be more reduced. On the other hand, being classified as cell-centre user implies that the user will be able to use a higher number of resources but with a lower SINR. The classification decision that maximizes the expected experienced throughput in a cell will depend on the network state at every moment. Experienced user throughput is estimated using the Shannon law, calculating narrowband SINR values considering as interference source the average long term received interference power.

Clustering procedure is solved in a completely distributed fashion, which allows a fast reconfiguration of clusters in case of network topology modifications. Every cell creates its own cluster, selecting the most $M-1$ interfering neighbours in a current instant. Clustering procedure can be triggered periodically or when network deployment is modified, that is, when a new

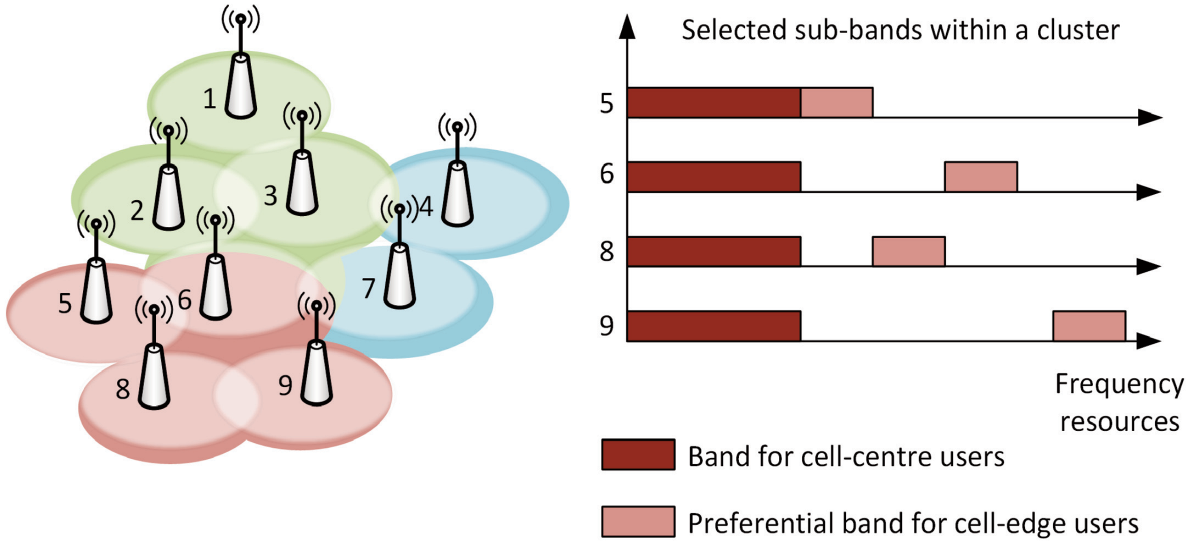


Figure 2. Clustering and selection of preferential bands in an irregular deployment.

PSEUDOCODE

```
Cell i switches on
Cell i selects M-1 neighbours to form its cluster

Cell i interrogates cells within its cluster and selects appropriate bands for cell-centre and cell-edge users
For each user j in cell i
        Calculates throughput if was classified as cell-edge user: Th_ce
        Calculates throughput if was classified as cell-centre user: Th_cc
        If Th_ce > Th_cc
            user j ⟹ cell-edge user
        else
            user j ⟹ cell-centre user
        end
End For each use
```

Table 1. Pseudocode.

cell has been activated or deactivated. Once the clustering is recalculated, the preferential sub-band allocation must be updated. Clustering procedure and user classification is summarized in Table 1.

3.1. Coordination among cells

As a good example of feasibility, direct cell-to-cell message exchange via the X2 interface [8] has recently been included in the LTE standard (from Release 10 on), although the information flow and interference mitigation mechanisms have not been clarified. Direct communication requires knowing the neighbour cells in advance. This is not a problem, since small cells are to be connected through gateways that could send a list with the IP directions of these neighbours. Once connected, small cells can coordinate themselves autonomously using messages like the LTE LOAD INDICATION procedure in the X2 Application Protocol (X2-AP). This procedure enables small cells to inform about their loads and interference conditions to neighbour cells. In the LTE downlink, a bitmap known as Relative Narrowband Transmit Power (RNTP) indicator can be also exchanged among small cells through this X2 interface. This ON-OFF indicator informs the neighbour cells if the cell intends to transmit on a certain RB over a certain power threshold or not. One bit per RB in the frequency domain is sent. The exact value of the upper limit and the periodicity in the reporting are configurable.

The use of the RNTP indicator allows small cells to choose the proper RBs when scheduling users according to the interference level introduced by their neighbours.

In the LTE uplink, two messages are exchanged: the Interference Overload Indication (IOI), which indicates the interference level on all RBs, and the High Interference Indication (HII), which informs about the future plans for the uplink transmission. The receiving cells should take this information into account not scheduling cell-edge users in these RBs.

This paper does not focus on the clustering selection, but it is important to stress that this kind of indicators can be used to autonomously create clusters and inform internally which the preferential resources to be used are. More details on this approach can be found in [9].

4. Simulation setup

Simulations are conducted considering an OFDM system composed by 60 small cells. The scenario has been defined following the guidelines described in [10] for ultra-dense deployments and consists of a building of 6 floors, where the dimensions of each floor are 120 m x 120 m.

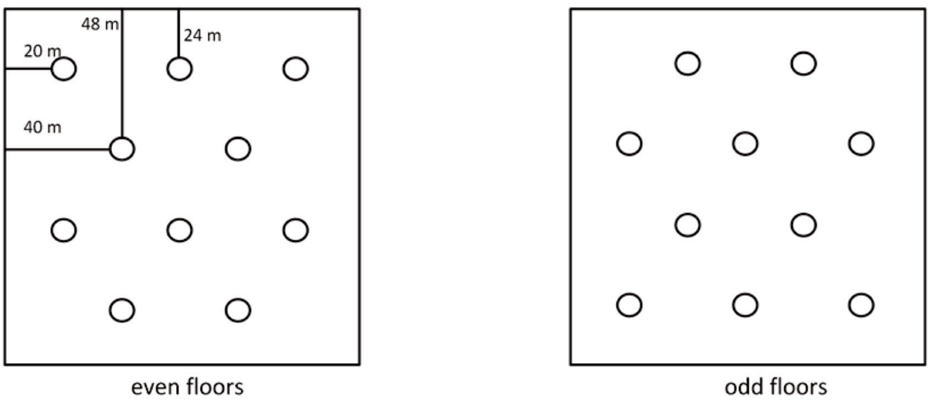


Figure 3. Small cells position on each floor of the building.

SYSTEM PARAMETERS AND VALUES			
Simulation time	**1 s**	**Carrier Frequency**	**2.6 GHz**
Number of drops	**10**	**System Bandwidth**	**20 MHz**
Number of users	**10-50/floor**	Δf	**180 kHz**
Number of small cells	**60**	**Nb of RBs**	**100**
Small cell transmission power	**20 dBm**	**Nb of fixed RBs per cell**	**40**
Traffic model	**Full buffer**	**Nb of preferential RBs per cell**	**10**

Table 2. System simulation parameters and values.

Height of each floor is 3.5 m. 10 small cells are uniformly distributed per floor. The position of the small cells on each floor depends on the floor level and is represented in Figure 3. Cell selection is performed based on received power. Simulations focus on the downlink. Other parameters used in the simulations are summarized in Table 2.

It is worth noting that once a user is allocated to a certain cell and sub-band, the cell operates autonomously without any coordination with the other cells inside the cluster. In this sense, coordination proposed in this paper can be classified as a joint scheduling technique.

5. Results

Results are presented comparing the proposed technique with the case in which no interference management technique is applied, considered the baseline. In Figure 4, the CDF of the average SINR per user is represented for different values of user density. Note that this SINR per user concept means the actual SINR experienced by the user in the RBs finally allocated for transmission. SINR values improve significantly with the application of the DLAD-FFR scheme. As it is expected, SINR values become lower as the number of deployed users per floor increases. This is because, as the number of users increase, we start allocating them in different cells of the cluster using the same RBs, which makes interference increase whereas signal level keeps the same. Also the gain in SINR when applying the DLAD-FFR scheme becomes smaller when the number of users per floor increases, what means that the FFR factor increases to allow the higher amount of users to be served. The median gain in SINR remains always above 3 dB. In the best case, with 10 users per floor, the gain is higher than 6 dB. Median SINR values and their corresponding gains can be checked in Table 3.

Thanks to the DLAD-FFR technique, not only interference is reduced but also the power consumption of the network. Average power necessary to serve a user is represented in Figure 5, normalized by the available power at each cell. It is worth to highlight that energy saving is over 25% in all cases and can be as high as 45% in some cases. As before, with less users DLAD-FFR is capable of distributing interferences within the cluster thus improving the SINR, which saves power consumption since data can be carried out with less resources. As the number of users increases then it is not so profitable to share the narrow preferential band and in the balance, they are assigned to the fixed bandwidth shared by all cells. This ends up reducing the energy savings, being the trend to no savings when the number of users tends to infinite.

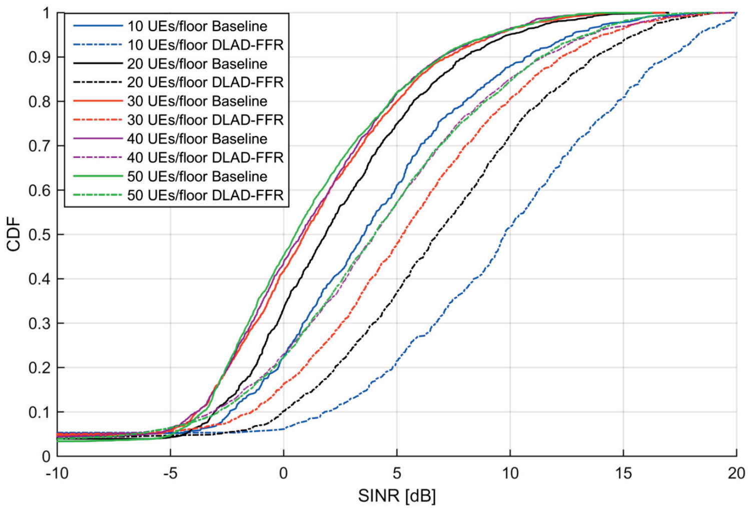
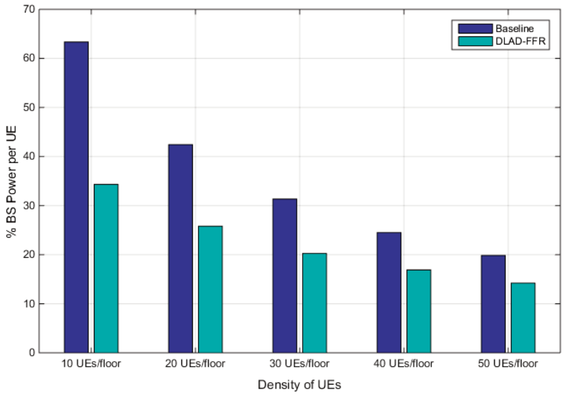
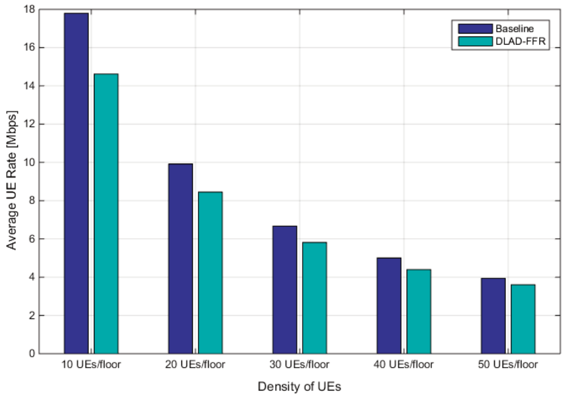


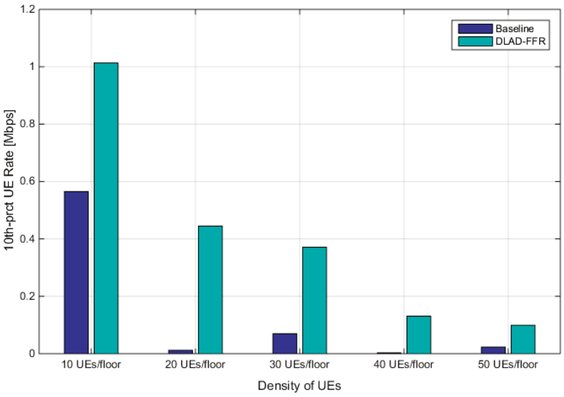
Figure 4. CDF of the SINR.



■ **Figure 5.** Power consumption.



■ **Figure 6.** Average UE rate.



■ **Figure 7.** 10th percentile UE rate.

Average rate per user and 10th percentile rate are represented in Figure 6 and Figure 7. As most of the ICIC techniques, DLAD-FFR achieves an improvement in cell-edge users' throughput at expenses of a reduction in the cell-centre users' rate. Relative gains of throughput are detailed in Table 5, where it can be appreciated that gains in 10th percentile rate are much bigger than the reduction in average rate that users suffered when the ICIC technique is applied. DLAD-FFR is able to increase cell-edge user throughput by a factor of 63, which results in a much higher fairness in the allocation of capacity within the network.

UEs/floor	SINR BL [dB]	SINR DLAD-FFR [dB]	Gain [dB]
10	3.55	9.77	+6.22
20	1.84	6.78	+4.94
30	0.92	5.25	+4.32
40	0.77	4.00	+3.22
50	0,51	4.01	+3.50

■ **Table 3.** SINR median values and absolute gain.

UEs/floor	Power per UE [%]		Saving
	BL	DLAD-FFR	[%]
10	63.33	34.33	-45.78
20	42.41	25.79	-39.18
30	31.33	20.23	-35.41
40	24.50	16.89	-31.05
50	19.83	14.21	-28.34

■ **Table 4.** Power consumption.

UEs/floor	Gain Avg Rate [%]	Gain 10th Prctl Rate [%]
10	-17.83	+79.19
20	-14.80	+3 732.79
30	-12.82	+434.10
40	-12.18	+4 523.39
50	-8.57	+328.78

■ **Table 5.** Average Rate.

6. Discussion and future work

In this work, a dynamic and load-adapting distributed FFR scheme for ultra-dense networks has been presented. System level simulations have shown that the described technique achieves a reduction in power consumption over the 25% while improving the SINR in more than 3 dB independently of the density of users deployed in the scenario. Furthermore, it has been shown that the implemented technique improves the fairness between the users, presenting a good compromise between cell-centre user average rate reduction and cell-edge rate increase. The proposed algorithm is able to adapt to the different load conditions, allocating users to the most appropriate band depending on the distribution of interference.

Some further simulations are left as future work, in order to check the performance of the algorithm when applied to non-homogeneous networks. Moreover, the behaviour of the algorithm in nomadic networks will be study.

Acknowledgments

The authors would like to thank the funding received from the Spanish Ministry of Science and Innovation within the Project number TEC2011-27723-C02-02.

References

[1] Damnjanovic, A.; Montojo, J.; Yongbin Wei; Tingfang Ji; Tao Luo; Vajapeyam, M.; Taesang Yoo; Osok Song; Malladi, D., "A survey on 3GPP heterogeneous networks," *Wireless Communications, IEEE* , vol.18, no.3, pp.10,21, June 2011 doi: 10.1109/MWC.2011.5876 496

[2] Bilios, D.; Bouras, C.; Kokkinos, V.; Papazois, A.; Tseliou, G., "Optimization of fractional frequency reuse in long term evolution networks," *Wireless Communications and Networking Conference (WCNC), 2012 IEEE* , vol., no., pp.1853,1857, 1-4 April 2012

[3] Mitran, P.; Rosenberg, C., "On fractional frequency reuse in imperfect cellular grids," *Wireless Communications and Networking Conference (WCNC), 2012 IEEE* , vol., no., pp.2967,2972, 1-4 April 2012 doi: 10.1109/WCNC.2012.6214312

[4] Ihalainen, T. ; Janis, P. ; Li, Z. ; Moisio, M. ; Nurmela, V. ; Uusitalo, M ; Wijting, C. ; Yilmaz, O., "Flexible scalable solutions for dense small cell networks", *Wireless World Research Forum (WWRF)*, 2013

[5] Shen, C.; Xu, J.; van der Schaar, M., "Silence is Gold: Strategic Interference Mitigation Using Tokens in Heterogeneous Small Cell Networks," *Selected Areas in Communications, IEEE Journal on* , vol.PP, no.99, pp.1,1, 2015.

[6] Shen, Z.; Andrews, J.G.; Evans, B.L., "Adaptive resource allocation in multiuser OFDM systems with proportional rate constraints," *Wireless Communications*, *IEEE Transactions on* , vol. 4, no. 6, pp. 2726–2737, 2005.

[7] Novlan, T.; Andrews, J.G.; Illsoo Sohn; Ganti, R.K.; Ghosh, A., "Comparison of Fractional Frequency Reuse Approaches in the OFDMA Cellular Downlink," *Global Telecommunications Conference (GLOBECOM 2010), 2010 IEEE* , Dec. 2010.

[8] 3rd Generation Partnership Project (3GPP). 3GPP TS 36.423, "X2 application protocol," March 2013.

[9] Giménez, S.; Monserrat, J. F.; Gómez, P.; Carrasco, O.; Cardona, N, "Realistic Implementation of X2-based Interference Management for LTE Femtocells,", Waves 2013, pp 5-13.

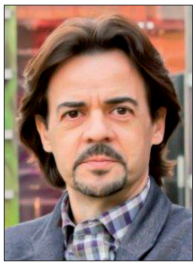
[10] Monserrat, J. F. (editor), "Simulation guidelines", ICT-317669 METIS project, D6.1, 2013.

Biographies

Sonia Giménez Colás received the Telecommunications Engineer degree and the M.Sc. degree in Communications Technologies, Systems and Networks from the Universitat Politècnica de València in 2009 and 2010, respectively. In 2009 she joined the Mobile Communications Group of the Institute for Telecommunications and Multimedia Applications at the Universitat Politècnica de Valencia. Now she is working towards the Ph. D and her research interests are focused on interference management in heterogeneous networks, especially in dense small cell deployments. In 2014 she visited the Fraunhofer Heinrich Hertz Institute, Berlin, for a period of three months. She is participating in the European project METIS (Mobile and wireless communications Enablers for the Twenty-twenty Information Society).

Daniel Calabuig was born in Valencia in 1981. He received the M.S. and Ph.D. degrees in telecommunications from the Universitat Politècnica de València in 2005 and 2010 respectively. In 2005 he joined the Institute of Telecommunications and Multimedia Applications (iTEAM) from the UPV. In 2006 he obtained a grant from the Spanish Ministry of Education for helping young researchers obtain their Ph.D. During the following years he participated in some European projects and activities like NEWCOM, COST2100 and ICARUS. Until finishing his Ph.D., Daniel Calabuig worked on radio resource management in heterogeneous wireless systems and Hopfield neural networks optimization. In 2009 he visited the Centre for Wireless Network Design (CWiND) at the University of Bedfordshire, Luton, UK, for a period of four months (CWiND is currently at the University of Sheffield). In 2010 he obtained a Marie Curie Fellowship from the European Commission for researching in the field of cooperative multipoint transmissions. Thanks to this fellowship, Daniel Calabuig visited the department of Systems and Computer Engineering (SCE) at Carleton University, Ottawa, Canada, from 2010 to 2012. During 2012, he also visited the TOBB Ekonomi ve Teknoloji Üniversitesi, Ankara, Turkey, for one month. He is currently involved in the European project Mobile and wireless communications Enablers for the Twenty-twenty Information Society (METIS), which main objective is lay the foundation of 5G, the next generation mobile and wireless communications system.

Dr. José F. Monserrat received his MSc. degree with High Honors and Ph.D. degree in Telecommunications engineering from the Polytechnic University of Valencia (UPV) in 2003 and 2007, respectively. He was the recipient of the First Regional Prize of Engineering Studies in 2003 for his outstanding student record receiving also the Best Thesis Prize from the UPV in 2008. In 2009 he was awarded with the best young researcher prize of Valencia. He is currently an associate professor in the Communications Department of the UPV. His research focuses on the application of complex computation techniques to Radio Resource Management (RRM) strategies and to the optimization of current and future mobile communications networks, as LTE-A and LTE-B. He has been involved in several European Projects, being especially significant his participation in WINNER+ where he leaded the research activities focused on the definition of Advanced RRM techniques for LTE-Advanced and in METIS where he is leading the definition of 5G simulation models. He also participated in 2010 in one external evaluation group within ITU-R on the performance assessment of the candidates for the future family of standards IMT-Advanced. He co-edited the February 2011 special issue on IMT-Advanced systems published in IEEE Communications Magazine and is co-author of the Wiley book "Mobile and wireless communications for IMT-Advanced and beyond"



Narcís Cardona MsC (1990), PhD (1995), Prof.(2001). Since October 1990 he is with the Communications Department of the Polytechnic University of Valencia (UPV), currently Full Professor on Signal Theory and Communications. Prof. Cardona is in head of the Mobile Communications Group at the UPV, with 30 researchers including assistant professors & research fellows. Additionally he is the Director of the Mobile Communications Master Degree (since 2006) and Vice-Director of the Research Institute of Telecommunications and Multimedia Applications (iTEAM) since 2004. Prof. Cardona has led National research projects and has participated in European projects, Networks of Excellence and other research forums in FP6, FP7 and H2020, always in Mobile Communications aspects. At European scale he has been Vice-Chairman of COST273 Action (2003-2006), Chair of the WG3 of COST2100 in the area of Radio Access Networks (2007-2010), and I am the Chairman of the EU Action COST IC1004 since May 2011, as well as member of the Board of METIS (7FP project on 5G Mobile Communications), since November 2011. His current research topics are Radio wave propagation, Planning and Optimisation of Mobile Access Networks (GSM, UMTS, LTE, 5G), Digital Multimedia (TV) Broadcasting, Spectrum Management and Wireless Body Area Networks.