Performance Assessment of Carrier Aggregation-Based Indoor Mobile Networks

Viktor R. Stoynov, Zlatka V. Valkova-Jarvis

Abstract**—**The intelligent management and optimisation of radio resource technologies will lead to a considerable improvement in the overall performance in Next Generation Networks (NGNs). Carrier Aggregation (CA) technology, also known as Spectrum Aggregation, enables more efficient use of the available spectrum by combining multiple Component Carriers (CCs) in a virtual wideband channel. LTE-A (Long Term Evolution–Advanced) CA technology can combine multiple adjacent or separate CCs in the same band or in different bands. In this way, increased data rates and dynamic load balancing can be achieved, resulting in a more reliable and efficient operation of mobile networks and the enabling of high bandwidth mobile services. In this paper, several distinct CA deployment strategies for the utilisation of spectrum bands are compared in indoor-outdoor scenarios, simulated via the recently-developed Realistic Indoor Environment Generator (RIEG). We analyse the performance of the User Equipment (UE) by integrating the average throughput, the level of fairness of radio resource allocation, and other parameters, into one summative assessment termed a Comparative Factor (CF). In addition, comparison of non-CA and CA indoor mobile networks is carried out under different load conditions: varying numbers and positions of UEs. The experimental results demonstrate that the CA technology can improve network performance, especially in the case of indoor scenarios. Additionally, we show that an increase of carrier frequency does not necessarily lead to improved CF values, due to high wall-penetration losses. The performance of users under bad-channel conditions, often located in the periphery of the cells, can be improved by intelligent CA location. Furthermore, a combination of such a deployment and effective radio resource allocation management with respect to user-fairness plays a crucial role in improving the performance of LTE-A networks.

Keywords**—**Comparative factor, carrier aggregation, indoor mobile network, resource allocation.

I. Introduction

THE recent switch from voice centric to data centric communication models, driven by user need, is leading to the wide usage of various multimedia devices such as smart phones, tablets, personal digital assistants (PDAs), and laptops. This inevitable trend generates increased demand for better performance from the new generation networks in terms of latency and capacity. In this context, new requirements for standardisation must be defined for modern communication technologies.

The characteristics of next generation communication technologies must be those that will ensure a high level of connectivity and an excellent quality of experience. With a view to meeting such requirements, an increase in spectral efficiency must be the main goal for the new advanced techniques that will appear over the next few years. In this context, a great flexibility in spectrum usage must be achieved. An important way to meet these requirements is through the use of CA. This is designed to increase the bandwidth and thus the bitrate, thereby creating the need for new access and management policies for multi-band and multi-bandwidth systems.

As a cellular paradigm, the enhanced heterogeneity of the networks in terms of the usage of different kinds of base stations operating at distinct low- or high-power levels leads to improved performance and capacity. The intelligent deployment of small (micro-) cells working in tandem with macro-cells contributes to the achievement of an excellent level of user connectivity, due to the reduced distance between the access points and the end-users. In addition, the Signal-to-Interference-Plus-Noise Ratio (SINR) associated with each UE has excellent values. However, the development of such Heterogeneous mobile Networks (HetNets) is challenging in several ways. First of all, the coverage disparities of the transmit nodes in HetNets cause uneven traffic loads across different layers, which makes the users within the network more sensitive to the cell association policies [1]. Additional interference may be generated in the network due to the simultaneous operation of many and varied sources of telecommunication signals: macro-cells, femto-cells, pico-cells, etc. Also, this may be exacerbated by the fact that often the femto-cells are distributed in an uncontrolled manner, especially in buildings. This could result in a deterioration of interference management and degradation of the services offered by mobile operators. In this context, a large amount of mobile traffic occurs in indoor environments, where many obstacles impact the signal propagation and thereby degrade the users' Quality of Service (QoS). These obstacles, often called blockages, may, according to their density, mitigate the interference or worsen the signal. Therefore, the use of multiple access points to provide uninterrupted coverage is a favoured approach. Low-power femto-cells are often distributed in confined spaces such as large houses, office buildings, shopping centres, etc. with the aim of increasing the performance of mobile services.

The performance of the UE depends on many factors, such as: scheduling algorithms, distance from the serving transmitter, the multipath environment, multiple antenna techniques, etc. In order to provide an excellent indoor QoS in line with users' needs, telecommunication service providers

V. R. Stoynov is with the Faculty of Telecommunications at the Technical University of Sofia, Bulgaria (corresponding author, phone: +359 883414611; e-mail: vstoynov@tu-sofia.bg).

Z. V. Valkova-Jarvis is with the Faculty of Telecommunications at the Technical University of Sofia, Bulgaria (e-mail: zvv@tu-sofia.bg).

need to apply Resource Allocation (RA) algorithms that ensure a high average user throughput (particularly for cell-edge users), good fairness with regard to radio resource distribution, and a lack of outages. The balance between these parameters is highly important in indoor environments (offices, shopping centres, markets, et al.), since the traffic demands are higher, and the signal propagation is worse. In this context, the implementation of CA functionality along with intelligent resource scheduling may improve the network performance in terms of spectral efficiency and QoS.

The main goal of this paper is to determine the level of performance that is achievable when CA is applied in collaboration with different scheduling algorithms. Several distinct scenarios in terms of different numbers of CCs and users are compared in indoor-outdoor environments realised by the RIEG. The simulation results are obtained by system level simulations using the Vienna LTE-A system level simulator [2], and the performance trends are discussed.

II. Related Work

A. Related Work

The authors in [3] examine the impact of spectrum aggregation technology on LTE network performance and more particularly on spectral efficiency, using system-level simulations. The analytical results obtained in this paper show that intra-band SA and contiguous carrier systems that use the same frequency band will achieve the same performance in an LTE system as long as no additional guard band is needed to avoid interference with adjacent channels.

In [4], a newly developed load-aware model for CA-enabled multi-band HetNets is introduced. Under this model, more precise characterisation of the impact of biasing is developed. As is widely known, biasing allows the low power nodes to artificially increase their transmit power. As a result, more UEs can be served by small cells and better traffic load balance can be achieved. Following the analysis, it transpires that the peak data rate does not depend on the base station density and transmit powers, and so an implementation of CA functionality can lead to an increase in peak data rate.

Multi-stage RA with CA algorithms are presented in [5]–[7]. The algorithm in [5] uses the Utility Proportional Fairness (UPF) approach to allocate the primary and secondary carriers' resources optimally between the mobile users in their coverage area. The primary carrier first allocates its resources optimally among users in its coverage area. The secondary carrier then starts allocating optimal rates to users in its coverage area based on the users' applications and the rates allocated to them by the primary carrier.

An RA with CA optimisation problem is presented in [6] to allocate resources from the LTE-A carrier and the MIMO radar carrier to each UE, in an LTE-A cell based on the application running on the UE.

A price selective centralised RA with CA algorithm is presented in [7], aiming to allocate multiple carriers' resources optimally among users while giving the user the ability to select one of the carriers to be its primary carrier and the others to be its secondary carriers. A price is set for each carrier, and each UE then makes a decision per unit bandwidth. However, the multi-stage RA with CA algorithms presented in [5]–[7] reach optimal rate allocation without achieving optimality in terms of pricing.

In [8], a Resource Block (RB) scheduling with CA approach in LTE-A is introduced. Users are split into groups, and each user is assigned RBs from the carriers which are in range. The authors compare the performance of the resource scheduling with CA approach in a case of two different kinds of scheduling. The first of these is the utility proportional fairness resource scheduling policy, and the second is the traditional proportional fairness (traditional-PF) scheduling policy presented earlier in [9]. The system model used for the simulations is however not sufficiently realistic to ensure the reliability of the resulting conclusions.

In [10], an efficient iterative RA algorithm was proposed for CA scenarios with large number of CCs. It was shown that the algorithm obtains the optimal RA solution under special cases of the RA problem, converges to binary-valued RA variables in the general case with only minor assumptions regarding the distribution of utilities, and outperforms heuristic RA schemes.

The authors of [11] analyse the performance gains and complexity level that arise from the aggregation of two and three inter-band component carriers (two CCs and three CCs) using a Vienna LTE System Level simulator. The results show a considerable increase in the average cell throughput when 3CC aggregations are implemented when compared to the 2CC aggregation. On the other hand, a reduction in the fairness index is also observed. Compensating for such a decrease in the fairness index could result in increased scheduler design complexity.

The work in [12] compared the performance of 2CC CA and 3CC CA, but used proprietary data, and equipment that makes it difficult for researchers to reproduce the work for the purposes of comparison and the exploration of further possibilities.

In [13], the authors consider two frequencies: 2 GHz and 5 GHz, which are used by the CA based network. At first, CCs were assigned to a lower frequency, then users with higher Channel Quality Indicator (CQI) values moved to a higher frequency based on the load of all other CCs. The load is calculated based on the availability of cell resources. This leads to increased computational complexity, and a multi-band approach is not considered.

In [14], the User Grouping PF (UG-PF) algorithm is proposed in order to improve fairness between users. In this model, path-loss with a certain threshold and coverage of each CC is calculated. Then, dependent on the number of available CCs which can be assigned to the users from their location, the users are divided into several groups. The cell-edge user groups are also allowed to access the RBs in the CCs of lower frequencies. Thus, the users with poor CQI value can obtain improved user throughput and fairness compared to the conventional PF algorithm. However, the average cell throughput can reduce when allocating many RBs to users with poor CQI.

A generalised PF algorithm based on the Cross-CC PF is proposed in [15]. It aims to balance the level of fairness between users with different aggregation capabilities and different channel conditions. This algorithm selects the CC for the users randomly and distributes the load across all CCs. It proves that when the CC selection is predetermined for a user, Cross-CC PF is a better scheduler to improve the throughput. Increased computational complexity is a drawback, due to the requirement for the exchange of data on previous user throughput for all CCs.

An absolute and relative policy is proposed in [16] by considering the signal quality of the CC. This method divides the cell coverage area into two different cells, named primary and secondary serving cells, with CCs respectively designated primary and secondary. The LTE-A user is attached to the eNB firstly with a primary cell, where the authors assume to have the best signal quality. According to their absolute or relative policies, when the signal quality of a CC is higher or lower than a predefined absolute or relative (defined by the use of offsets) threshold, the CC is added to or removed from the resources available to the user as appropriate. The drawback of the paper is that it is extremely difficult to determine the optimal threshold or offset values.

In [17], a new ambitious method is proposed with the aim of maximising the throughput using a PF packet scheduling algorithm. This method considers link adaptation jointly with CC assignment and RB allocation. After calculating the gain of all possible combinations, CCs are assigned to the users which have the highest gain. The authors assumed, unrealistically, that all CCs have an equal number of RB and all users have similar capabilities.

III. CA Basics

CA consists of aggregating several spectrum bands into a single larger virtual band. The use of CA results in higher available data rates, but more complex and expensive transceivers have to be used. Likewise, CA can also lead to better resource utilisation and spectrum efficiency by means of joint RA and load balancing across the carriers. The scheme is already part of commercial networks aiming to offer double data rates and is in competition with 4G systems.

The CA implementation in new generation networks can lead to a major technological advance in regard to LTE-A systems. Multiple CCs with varying bandwidth, dispersed within inter- and intra-bands, can be utilised through spectrum aggregation in a simultaneous manner to achieve better coverage, high data rates, lower latency, and excellent user throughput.

The big design challenge, however, is the intelligent decision of which, and how many, bands need to be used in order to satisfy the requirements. Implementation complexity needs to be addressed with novel optimal CC selection methods required, as well as consideration of both RB scheduling and the CC selection.

There are three different types of CA. The first one, Intra-band contiguous CA, makes use of the same operating frequency band. The resultant overall bandwidth is more than 20 MHz, and there are certain to be adjacent CCs [18]. When Intra-band non-contiguous CA is applied, multiple non-contiguous carriers belonging to the same frequency band are used. This type of CA is more complicated as multi-carrier signals cannot be assumed to be a single signal, and thus, two transceivers are needed [19]. The last type, Inter-band non-contiguous CA, allows different frequency bands, such as 800 MHz and 2 GHz, to be used at the same time. The use of two or more carriers can greatly improve the communication throughput and the stability of signal propagation in urban and sub-urban environments characterised by the existence of many obstacles [20]. The main drawback of this CA utilisation scenario is, however, the complexities due to the requirement to minimise cross modulation and intermodulation from the transceivers.

In this paper, a total number of five CCs working on five different frequencies is used. Thus, the impact of different numbers of CCs can be defined when indoor-outdoor scenarios are considered.

IV. Downlink RA Algorithms

The scheduling RA algorithms can be summarised into two types: Channel-Independent Scheduling (CIS) and Channel-Dependent Scheduling (CDS). In this work, the second type of RA algorithms is used. As is widely known, the CDS strategy is based on optimal algorithms and can thus achieve a better performance in allocating resources, since information about the channel quality is available. The CIS strategy can never provide an optimal solution in a wireless network, due to the lack of information about channel conditions.

Fairness is improved when the PF algorithm is applied, and the average throughput is preserved, i.e. efficiency is retained. A priority function is calculated as a ratio of the instantaneous to average throughput and is used to prioritise the UEs. The highest priority user is allocated resources, then the priority function is re-calculated, and another UE gets the highest rank. The algorithm repeats until either all the UEs' needs are satisfied, or the resources are exhausted.

A method called SBQMM-PF (SINR Based Quantile Mean Method in Proportional Fair) based on instantaneous user SINR values is presented in this paper. It aims to achieve a fairer distribution of network resources compared to the widely used PF algorithm by modifying it. Depending on the value of the SINR of each user in each Transmission Time Interval (TTI), a choice is made between two of the Quantile Averaging Methods (QAM) presented in [21]: 3-min+max and 2-min. The quantiles theory is applied to the dataset of throughputs for each user for each TTI, after they are sorted into ascending order. To obtain 3-min+max QAM, the dataset is divided into four equal groups. Then, the arithmetic means of the min and max group are summed. In the case of the 2-min method, the dataset is divided into two equal groups by the median value. Then, the arithmetic mean of the min group is obtained.

According to the results in [21], the 2-min method achieves the best levels of fairness of RA. On the other hand, the usage of 3-min+max leads to a very unfair distribution of system resources, especially when the number of users increases. By contrast, this method works very well for cell-centre users, providing them with more resources and resulting in excellent values for the UE average throughput.

The use of the two methods described above aims to increase the performance of users with low SINR, which are often far from their serving cell and thus subject to high levels of interference from nearby cells. The threshold value of SINR, ΩSINR, is chosen to be the median value of the set of SINR values for all users in the particular TTI. For users with SINR less than ΩSINR, the 3-min+max applies, as it aims to maximise user productivity, also taking into account the fairness of network RA. For users with SINR equal to or greater than ΩSINR, the 2-min method is applied, this being one of the fairest in terms of RA. When using the PF algorithm, TPF = 1 is chosen to ensure that the maximum values of fair allocation of resources available for the algorithm are reached. The simulation research aims to optimise the fairness and QoS for users located at the periphery of the serving cell.

V. System Model

A. Network Design

A realistic indoor environment comprising constant femto-cell locations and different numbers of users was employed in order to compare the performance of different RA algorithms when CA is enabled. Indoor-outdoor design simulations were conducted, using the RIEG wall pattern method presented by the authors in [22]. This method distributes rectangles in order to model a floorplan with multiple rooms and corridors. The coordinates of the starting point of each rectangle are selected randomly. The sides of the rectangle are then plotted, ensuring that the rectangle remains within the simulated enclosed space named Region of Interest - RoI. The investigations in [22] showed that the RIEG wall arrangement method is the closest to a real-world scenario and is realistic enough to be used as an indoor environment to test interference suppression techniques and algorithms for realistic human mobility and intelligent RA.

Two basic parameters, wall density λ and wall attenuation ω, characterise the arrangement of the walls. The length of the walls per square metre is defined by the wall density, and the impact of the walls on signal propagation by the wall attenuation.

Fig. 1 shows the indoor-outdoor network environment layout (RoI). The circles denote the femto-cells and the dots represent the locations of the UEs.

B. Comparative Factor

The CF previously introduced in [22] is a metric which simultaneously takes into account four distinct performance parameters: normalised average user throughput (*F*1), normalised average cell-edge user throughput (*F*2), fairness (*F*3) and outage ratio (*F*4):

$$F = F_1 + F_2 + F_3 - F_4 \quad (1)$$

In order to provide a meaningful CF value, all four parameters are structured to take values from 0 to 1, so that the CF will range from -1 to 3. Normalisation against experimentally-obtained reference peak user throughputs is employed to transform the average user throughputs of all users and the average cell-edge user throughputs into a dimensionless ratio [22]. Thus, *F*1 and *F*2 take values from 0 to 1.

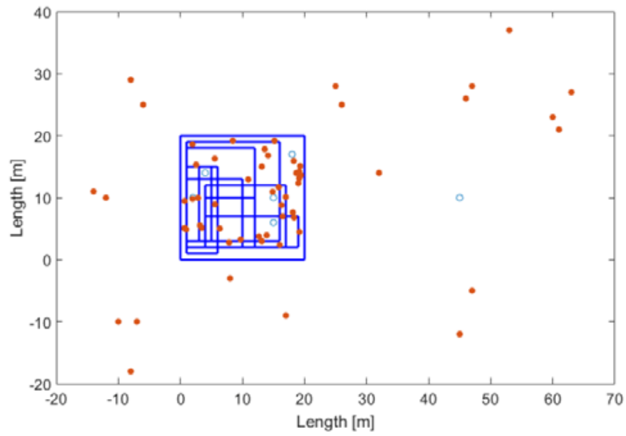

Fig. 1 Network layout modelled by RIEG

*F*3 describes the level of fairness of RA among the users in the particular mobile network that is under investigation. It is a well-known fact that an unfair RA between different UEs may result in resource starvation, resource wastage, or redundant allocation.

The fourth parameter comprising the CF is the outage ratio, *F*4. It represents the ratio of the number of users with outages to the total number of users. In this study, due to the specifics of the RA algorithms being simulated, *F*4 has a constant value of 0.

VI. System-Level Simulation Results

A. Simulation Setup

The experiments were carried out using a constant number of 5 femto-cells and different numbers of users: 20 outdoor users and 20 or 40 indoor users. Each of the simulations had a duration of 100 s, equal to 100000 identical TTIs. This ensures the reliability of the results obtained. A floor plan of acceptable realism was modelled with the RIEG wall layout. The traffic model was set to full buffer, which ensures that data are being transmitted at any given time. It was also assumed that there was an external source of interference – an outdoor macro BS. The femto-cells are working in Open Subscriber Group (OSG). Thus, the macro-users are also permitted to be associated to the femto-cells located indoors. This leads to decreased interference, especially when compared to the Closed Subscriber Group (CSG) scenario. All parameters had the same value in each simulation, thus helping to obtain reliable results. The numerical values of the simulation parameters are given in Table I.

The component carrier CC1 serves only users connected to the macro-cell, while CC2, CC3 and CC4 and CC5 are reserved exclusively for the users located in the enclosed space simulating real building and which are served by femto-cells.

TABLE I
PARAMETERS AND THEIR NUMERICAL VALUES

Quantity	Conversion from Gaussian and CGS EMU to SI [a]
CC1 frequency	2.6 GHz
CC2 frequency	2.3 GHz
CC3 frequency	0.8 GHz
CC4 frequency	2.1 GHz
CC5 frequency	3.5 GHz
Frequency (without CA)	2.6 GHz
Bandwidth for CC1. CC2. CC3. CC4 and CC5	20 MHz
Bandwidth (without CA)	20 MHz
Number of RBs	100
Simulation duration	100000 TTI (100s)
Transmission mode	CLSM
Femto-cell transmission power	1 W
Number of users	40 (20/20), 60 (40/20)
Number of femto-cells	5
Femto-cell mode of operation	Open Subscriber Group (OSG)
Wall Density	0.2 m^{-2}
Wall Attenuation level	10 dB
Dimensions (ROI)	90 m x 60 m
Indoor environment dimensions (ROI)	20 m x 20 m
Traffic model	Full buffer

Four distinct scenarios are defined in this study:

[S1] = {20 outdoor users, 20 indoor users, without CA};
[S2] = {20 outdoor users, 40 indoor users, without CA};
[S3] = {20 outdoor users, 20 indoor users, with CA};
[S4] = {20 outdoor users, 40 indoor users, with CA}.

B. Simulation Results and Analysis

The comparison of the PF and SBQMM-PF in terms of fairness and average UE throughputs with a different number of indoor users and a constant number of outdoor users is shown in Tables II and III.

TABLE II
COMPARISON OF PF AND SBQMM-PF, 20 INDOOR AND 20 OUTDOOR USERS

	Fairness	
Mode	PF algorithm	SBQMM-PF algorithm
Without CA	0.65	0.58
With 3 CC	0.5	0.47
With 5 CC	0.43	0.53
	Average User Throughput	
Mode	PF algorithm	SBQMM-PF algorithm
Without CA	10.97	13.36
With 3 CC	7.91	9.08
With 5 CC	10.54	11.55

Experimental numerical results for CF are shown in Table IV. The markings "F", "M" and "F+M" denote respectively the value of CF obtained for femto-users, macro-users and all users.

The experimental results for average UE throughputs are depicted in Figs. 2-7. The comparison of the scenarios is plotted graphically, with the CDF being the reference axis. This function reflects the distribution of the relevant parameter and is not a probability function. During simulation, the UE throughput values achieved by each user are recorded in a database. The graphs represent the distribution of these values, with the CDF changing from 0 to 1, which corresponds to the rate of occurrence of the respective test parameter in percentages from 0 to 100%.

TABLE III
COMPARISON OF PF AND SBQMM-PF, 40 INDOOR AND 20 OUTDOOR USERS

	Fairness	
Mode	PF algorithm	SBQMM-PF algorithm
Without CA	0.62	0.57
With 3 CC	0.46	0.53
With 5 CC	0.60	0.60
	Average User Throughput	
Mode	PF algorithm	SBQMM-PF algorithm
Without CA	9.63	12.34
With 3 CC	4.13	4.21
With 5 CC	5.19	6.28

TABLE IV
COMPARISON OF PF AND SBQMM-PF, 20/40 INDOOR AND 20 OUTDOOR USERS – RESULTS FOR CF

	20 indoor and 20 outdoor users					
Mode	PF algorithm			SBQMM-PF algorithm		
	F	M	F+M	F	M	F+M
Without CA	1.485	1.643	1.225	1.637	1.09	0.96
With 3 CC	1.227	0.72	1.145	1.158	1.11	1.12
With 5 CC	1.237	1.12	1.029	1.029	1.02	1.01
	40 indoor and 20 outdoor users					
Mode	PF algorithm			SBQMM-PF algorithm		
	F	M	F+M	F	M	F+M
Without CA	1.4	1.31	1.15	1.121	0.882	0.958
With 3 CC	1.305	0.959	1.197	1.37	1.148	1.344
With 5 CC	1.266	1.041	1.168	1.394	1.017	1.269

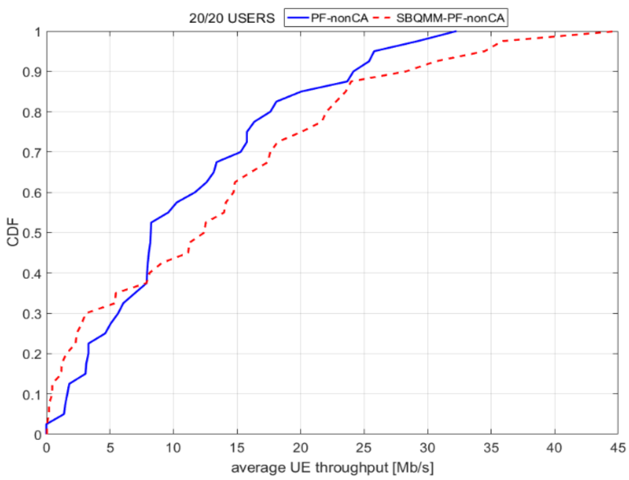

Fig. 2 Average UE throughput results for **[S1]** – without CA functionality

The developed SBQMM-PF algorithm achieves better results than the PF algorithm, regardless of the number of users and presence of CA functionality. The levels of fairness in allocating the resources achieved by the two algorithms are similar in value, but the proposed SBQMM-PF algorithm features higher levels of average throughput (Tables II and III). When a traditional scenario without CA is considered, SBQMM-PF shows a clearly better performance compared to the traditionally used PF algorithm (Figs. 2 and 5). It turns out that when different numbers of indoor users are considered, there is no stability in the CFs of either of the methods examined (Table IV). In this context, the SBQMM-PF algorithm should be improved in regard to a more intelligent RA. This can be achieved by better traffic load balance or by favouring certain types of users allocated to femto- or macro-cells.

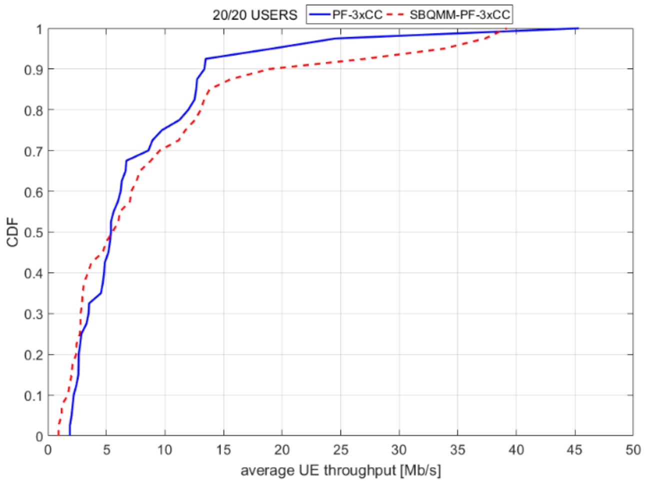

Fig. 3 Average UE throughput results for **[S3]** – with three CCs

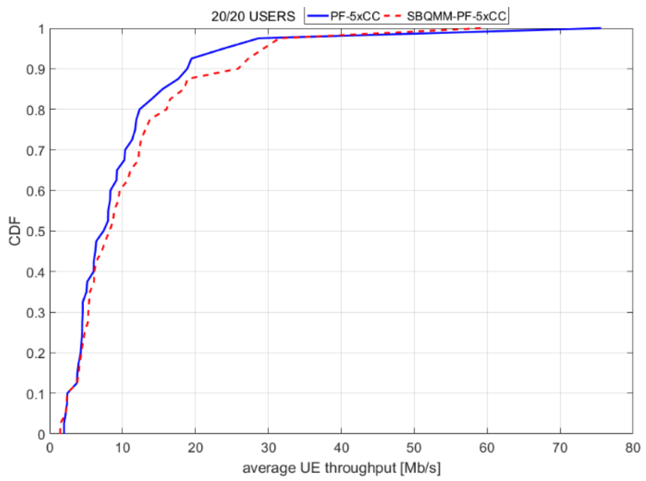

Fig. 4 Average UE throughput results for **[S3]** – with five CCs

Once the CA functionality is enabled, the SBQMM-PF clearly shows an improved performance in comparison to the conventional PF algorithm (Table IV). This trend becomes more visible when the number of users increases. The performance of SBQMM-PF lacks stability when scenarios **[S1]** and **[S3]** are considered. Obviously a more precise determination of the SINR threshold value Ω_{SINR} would result in better performance despite the varying number of active users. Hence, the use of CF provides the possibility for more detailed analysis of the behaviour of the algorithms.

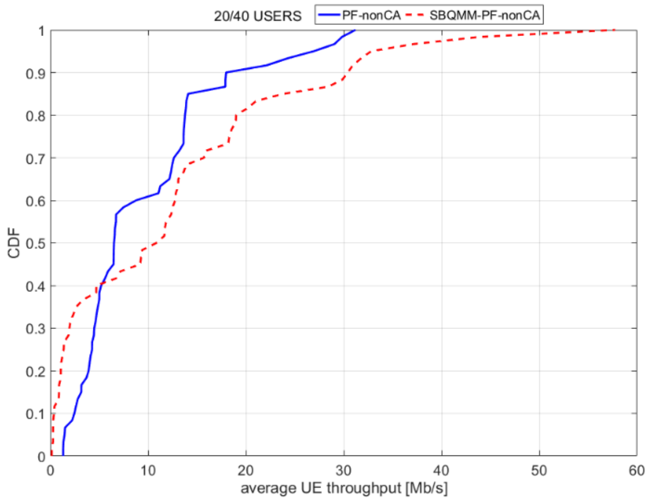

Fig. 5 Average UE throughput results for **[S2]** – without CA functionality

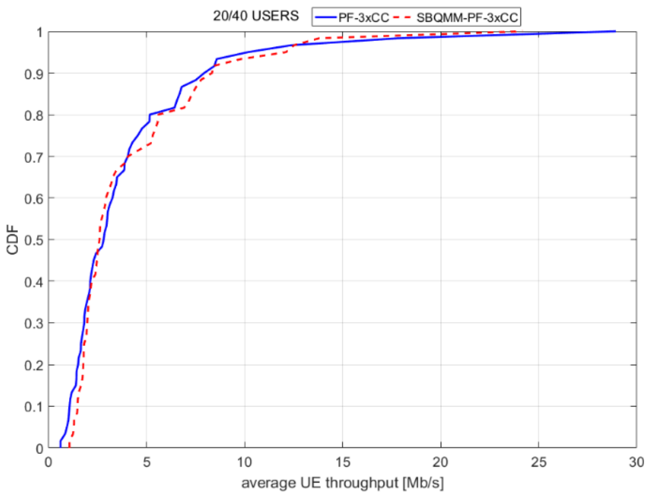

Fig. 6 Average UE throughput results for **[S4]** – with three CCs

Upon consideration of the figures, it can be seen that when an increased number of users is observed, i.e. if there is a higher traffic load, CA has less of an impact (Figs. 3, 4, 6 and 7). In the other words, the use of this technology does not always give significantly better results in terms of overall network performance. In this case, the main reason for this behaviour is the use of the OSG mode of operation in the femto-cells. Unlike the situation with CSG, the interference in the network is much smaller and in turn the impact of CA is far less noticeable. In this context, the intelligent use of CAs can reduce the costs of the mobile operator. The creation of an algorithm to dynamically determine the number of CCs, depending on the mobile network peculiarities such as the presence of buildings, the number of users, the traffic load, the UEs' SINRs and the cell types from which it is built, will be the goal of future research.

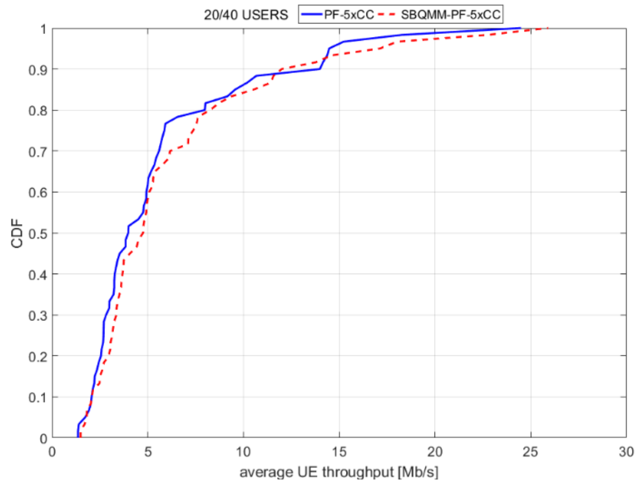

Fig. 7 Average UE throughput results for **[S4]** – with five CCs

It is an interesting fact that when CA functionality is enabled the fairness of RA is slightly reduced. Also, when three CCs are used lower values for the average UE throughput are observed compared to the scenarios when no CA functionality is considered (Tables II and III). This is due to the fact that the first two CCs have similar frequency values. This is chosen to show the interference which occurs when such frequencies are selected. Therefore, a more intelligent algorithm must be designed in order to minimise the probability of interference occurring in the mobile network by distributing the CCs among the users in a smarter way. It should take into account both the distance between the users and their access points, together with the level of interference in the specific RoI.

The full buffer traffic model used during the simulations results in a maximum load on the mobile network. In this way, the SBQMM manages to optimise network performance despite the aggressive traffic load that is observed in all the scenarios studied in this paper.

VII. Conclusion

In this paper, an improvement to the widely known PF algorithm, in terms of an excellent balance between fairness and UE throughput, is presented. The SBQMM-PF succeeds in maximising the UE throughput of the users in indoor-outdoor scenarios when CA is performed without sacrificing the fairness of resource distribution.

The simulation-based investigation conducted in this paper leads to several important conclusions. Firstly, more work is required in order to enhance the SBQMM-PF performance in terms of intelligent CC selection and distribution among the users. Secondly, further analytical and simulation tests are needed to fine-tune the optimal combination of quantile methods to be used in SBQMM-PF. In addition, this needs to be compared against other well-known RA algorithms designed to work in mobile networks with existing CA functionality.

The SBQMM-PF has to be upgraded in terms of a more intelligent way to determine the optimal value of Ω_{SINR} in specific traffic conditions.

Generally speaking, more deep research into indoor scenarios of signal propagation needs to be conducted by engineers in order to enhance the performance of NGNs.

Acknowledgment

The paper is published with the support of the project No **BG05M2OP001-2.009-0033** "Promotion of Contemporary Research Through Creation of Scientific and Innovative Environment to Encourage Young Researchers in Technical University - Sofia and The National Railway Infrastructure Company in The Field of Engineering Science and Technology Development" within the Intelligent Growth Science and Education Operational Programme co-funded by the European Structural and Investment Funds of the European Union.

References

[1] D. Lopez-Perez, X. Chu; I. Guvenc, "On the Expanded Region of Picocells in Heterogeneous Networks," IEEE J. Sel. Top. Signal Process. 2012, 6, pp. 281–294.

[2] M. Rupp, S. Schwarz, and M. Taranetz, The Vienna LTE Advanced Simulators: Up and Downlink, Link and System Level Simulation, 1st ed., ser. Signals and Communication Technology. Springer Singapore, 2016.

[3] M. Alotaibi, M. Sirbu, and J. Peha, ''Impact of spectrum aggregation technology and frequency on cellular networks performance,'' in Proc. IEEE Conf. Dyn. Spectr. Access Netw. (DySPAN), Sept./Oct. 2015, pp. 326–335.

[4] X. Lin, J. G. Andrews, A. Ghosh, "Modeling analysis and design for carrier aggregation in heterogeneous cellular networks," *IEEE Trans. Commun.*, vol. 61, no. 9, pp. 4002-4015, Sep. 2013.

[5] H. Shajaiah, A. Abdel-Hadi, and C. Clancy, "Utility Proportional Fairness Resource Allocation with Carrier Aggregation in 4G-LTE," in Military Communications Conference, MILCOM 2013 - 2013 IEEE, pp. 412–417, Nov 2013.

[6] H. Shajaiah, A. Khawar, A. Abdel-Hadi, and T. Clancy, "Resource allocation with carrier aggregation in LTE Advanced cellular system sharing spectrum with S-band radar," in Dynamic Spectrum Access Networks (DYSPAN), 2014 IEEE International Symposium on, pp. 34–37, April 2014.

[7] H. Shajaiah, A. Abdelhadi, and T. C. Clancy, "A price selective centralized algorithm for resource allocation with carrier aggregation in LTE cellular networks," arXiv: 1408.4151, Accepted in WCNC, 2015.

[8] H. Shajaiah, A. Abdelhadi, T. C. Clancy, "Towards an application-aware resource scheduling with carrier aggregation in cellular systems," IEEE Commun. Lett., vol. 20, no. 1, pp. 129-132, Jan. 2016.

[9] I.-H. Hou and C. S. Chen, "Self-organized resource allocation in LTE systems with weighted proportional fairness," in Communications (ICC), 2012 IEEE International Conference on, pp. 5348–5353, June 2012.

[10] S. Stefanatos, F. Foukalas; T.A. Tsiftsis, "Low Complexity Resource Allocation for Massive Carrier Aggregation". IEEE Trans. Veh. Technol., 66, pp. 9614–9619, 2017.

[11] L. Kiwoli, S. Anael, E. Manasseh, "Performance Analysis of Carrier Aggregation for Various Mobile Network Implementations Scenario Based on Spectrum Allocated," International Journal of Wireless & Mobile Networks, pp. 41-53, 2017.

[12] A. Tanner, Master Thesis on "LTE-A 3CC carrier aggregation," Helsinki Metropolia University of Applied Sciences, May, 2016.

[13] F. Meucci; O. Cabral; F.J. Velez; A. Mihovska; N.R. Prasad, "Spectrum aggregation with multi-band user allocation over two frequency bands,". In Proceedings of the IEEE MobileWiMAX Symposium, Napa, CA, USA, 9–10 July 2009; pp. 81–86.

[14] S. Songsong, F. Chunyan; G. A. Caili, "Resource Scheduling Algorithm Based on User Grouping for LTE-advanced System with Carrier

Aggregation," in Proceedings of the International Symposium on Computer Network and Multimedia Technology (CNMT 2009), Wuhan, China, 18–20 December 2009; pp. 1–4.
[15] Y. Wang, K. Pedersen, P. E. Mogensen, T.B. Sørensen, "Resource allocation considerations for multi-carrier LTE-Advanced systems operating in backward compatible mode," in Proceedings of the IEEE 20th International Symposium on Personal, Indoor and Mobile Radio Communications, Toyko, Japan, 13–16 September 2009; pp. 370–374.
[16] L. Liu, M. Li, et al., "Component carrier management for carrier aggregation in LTE-advanced system", in Proceedings of the IEEE 73rd Vehicular Technology Conference (VTC Spring), Budapest, Hungary, 15–18 May 2011; pp. 1–6.
[17] H.-S. Liao, P.Y. Chen, W.-T. Chen, "An efficient downlink radio resource allocation with carrier aggregation in LTE-advanced networks," IEEE Trans. Mob. Comput. 2014, vol. 13, pp. 2229–2239.
[18] E. Dahlman, S. Parkvall and J. Sköld, 4G LTE/LTE-Advanced for Mobile Broadband, Oxford: Academic Press, 2011.
[19] M. Al-Shibly, M. Habaebi and J. Chebil, "Carrier Aggregation in Long Term Evolution-Advanced," in Control and System Graduate Research Colloquium (ICSGRC), Shah Alam, Selangor, 2012.
[20] L. Liu, M. Li, J. Zhou, X. She, L. Chen, Y. Sagae and M. Iwamura, "Component Carrier Management for Carrier Aggregation in LTE Advanced System," in Vehicular Technology Conference (VTC Spring), Budapest, 2011.
[21] Z. Valkova-Jarvis, V. Stoynov, "Novel Throughput Quantile Averaging Methods for the Proportional Fair Algorithm in Indoor Mobile Networks," 2017 Advances in Wireless and Optical Communications (RTUWO), Riga, Latvia, 2-3 November, 2017, pp.198 - 202.
[22] V. Stoynov, Z.Valkova-Jarvis, "Aggregated Assessment of Downlink Resource Scheduling Techniques in Indoor Environments via a Comparative Factor," ELMAR 2017, Zadar, Croatia, 18-20 September, 2017, pp. 185-188.