Co-Primary Spectrum Sharing in Uplink SC-FDMA Networks

Dionysia Triantafyllopoulou, Seiamak Vahid and Klaus Moessner
5G Innovation Centre (5GIC)
Institute for Communication Systems (ICS)
University of Surrey
Guildford, Surrey, GU2 7XH, United Kingdom
Email: {d.triantafyllopoulou, s.vahid, k.moessner}@surrey.ac.uk

Abstract—In this paper we present a co-primary spectrum sharing algorithm for the Quality of Service (QoS) enhancement of uplink Single-Carrier Frequency Division Multiple Access (SC-FDMA) systems. We consider the limitations that are resulting from the fact that each user can only be provided with only contiguous sets of resource blocks (following the constraints of the localized SC-FDMA physical layer), and the effect of the limited, or even lack of, knowledge of each user's buffer status and packet delays in the uplink. The sharing of available resources is based on the operator spectrum access priority, an estimation of the packet delays in the uplink direction, the average delay and data rate of earlier allocations, and the power per resource block. Simulation results show that the proposed algorithm considerably improves the performance in terms of packet loss rate, goodput, and fairness.

I. INTRODUCTION

One of the solutions considered to address the increased demand for wireless spectrum resources is the utilisation of licensed spectrum in a shared manner. One type of co-primary spectrum sharing considers the simultaneous access of a licensed band by a number of Mobile Network Operators (MNOs), under bi/multi-lateral agreements that guarantee fair spectrum access.

In the relevant literature, a number of contributions on licensed spectrum sharing can be found. The majority of them only consider the channel quality information (CQI), and not the more relevant Quality of Service (QoS)-related metrics for spectrum sharing [1]–[4]. A typical assumption considers the use of a centralised controller that is responsible for the management of the sharing procedure in a common pool of shared spectrum between two MNOs, introducing increased complexity and signaling overhead [1]. A cooperative spectrum sharing scheme between two MNOs that employ infrastructure sharing is proposed in [2]. The spectrum pool includes dedicated spectrum for each MNO, and the shared spectrum. The partitioning of the spectrum to orthogonally and non-orthogonally shared frequency sub-bands is performed adaptively, based on the channel conditions of the users. Spectrum sharing is performed considering the CQI, and not more QoS-related metrics.

In cases where beamforming is used [3], [4], where the spectrum pool is available for simultaneous access by two MNOs in the same area, the major challenges relate to strict timing requirements and the accuracy of CQI exchanged between base stations. Even works that consider user throughput and fairness, e.g., [5], do not evaluate the impact of sharing on the mean delay. Specifically, [5] considers a common pool of radio resources, shared by a multi-operator small cell network, aiming to achieve long term fairness. A decentralised mechanism is used to allocate the appropriate amount of spectrum to each access point. The main performance metrics are user throughput and fairness between operators.

Motivated by the above, this paper extends the resource allocation algorithm of [6], to propose a QoS-oriented co-primary spectrum sharing algorithm for uplink Single-Carrier Frequency Division Multiple Access (SC-FDMA) systems. The allocation of the shared resources is based on the MNO priority, an estimation of the packet delays in the uplink direction, the average delay and data rate of earlier allocations, as well as the power per resource block (RB) in the uplink.

The novelties of this paper are the following:

- 1) The proposed work considers the limitations of uplink resource allocation, and consequently spectrum sharing, in a realistic Long Term Evolution (LTE) system. These include the constraint to allocate only contiguous RB sets to each user, due to the localized SC-FDMA physical layer, and the procedures followed by the users in order to request for uplink transmission grants and report their buffer status, as described in LTE specifications. This allows for the reduction of resource waste, by not allocating more resources than the users actually need, resulting in a more efficient resource sharing.
- 2) The spectrum sharing process considers the delay constraints of real-time applications, by estimating the uplink packet delays from the received user Scheduling Requests (SRs). Therefore, users

experiencing excessive delays are prioritized, reducing the probability of real-time packet expirations and resulting in improved QoS provision.

The structure of this paper is the following. Section II briefly describes the system model. Section III introduces the proposed spectrum sharing algorithm. Performance evaluation results are presented in Section IV. Section V provides conclusions and plans for future work.

II. SYSTEM MODEL

We consider a pool of shared spectrum for the uplink traffic, in the case of MNOs employing infrastructure sharing. The size of the shared spectrum pool equals to the sum of the total holdings of the partaking MNOs. An LTE cell is considered, with a number of randomly deployed user equipment (UE) devices, each one associated with an MNO.

III. THE PROPOSED ALGORITHM

The problem of optimal allocation of uplink scheduling blocks (SBs), i.e., two consecutive RBs spanning a subframe of length equal to T_{sf} , in localized SC-FDMA is shown to be NP-hard in [6]. Therefore, we introduce the following suboptimal algorithm to address the resource sharing. To evaluate the utility of each SB of the shared spectrum pool to the users of each MNO, we introduce metric $m_{i,j,k}^{UL}(t)$ of user i , $i \in UE$, who is a subscriber of MNO k , for SB j , $j \in 1, 2, \dots, N_{SB}$, where N_{SB} is the number of SBs per subframe of the shared spectrum, as follows:

$$m_{i,j,k}^{UL}(t) = p_k \frac{d_{i,k}^{UL}(t)}{d_{th,i,k}} \exp\left(\frac{\bar{D}_{i,k}^{UL}(t)}{\bar{R}_{i,k}^{UL}(t)}\right) \times \frac{1}{P_{1,i,k} \cdot N_{RB,SB}} r_{i,j,k}^{UL}(t). \quad (1)$$

where p_k denotes the shared spectrum access priority of MNO k , whose value can be proportional to the size of the spectrum contributed to the pool by each MNO. $d_{i,k}^{UL}(t)$ estimates the delay of user i , based on the time passed since he was provided with an uplink grant, or he last sent a SR. $d_{th,i,k}$ is the delay threshold, i.e., if the delay of a packet of a real-time application exceeds this, the packet is no longer useful to the receiver and it is discarded. $\bar{D}_{i,k}^{UL}(t)$ and $\bar{R}_{i,k}^{UL}(t)$ are the average delay and data rate, respectively, of the earlier allocations to user i . A weighted moving average formula is used for their calculation as follows:

$$\bar{D}_{i,k}^{UL}(t) = \beta d_{i,k}^{UL}(t) + (1 - \beta) \bar{D}_{i,k}^{UL}(t - 1), \quad (2)$$

$$\bar{R}_{i,k}^{UL}(t) = \beta r_{i,k}^{UL}(t) + (1 - \beta) \bar{R}_{i,k}^{UL}(t - 1), \quad (3)$$

where $r_{i,k}^{UL}(t)$ is the instantaneous uplink data rate of user i and $0 \leq \beta \leq 1$. $P_{1,i,k}$ is the minimum uplink power per RB of user i [6]:

$$P_{1,i,k} = \min \{P_{CMAX,C}, P_{0,PUSCH} + \alpha PL_{i,k} + 10 \log_{10}(N_{RB}^{UL})\} - 10 \log_{10} N_{RB}^{UL}. \quad (4)$$

$r_{i,j,k}^{UL}(t)$ is the data rate of user i on SB j :

$$r_{i,j,k}^{UL}(t) = (L_{SB}^{UL} \log_2 M_{i,j,k}) / T_{sf}, \quad (5)$$

where L_{SB}^{UL} is the number of resource elements per uplink SB that are responsible for data transfers, and $M_{i,j,k}$ is the Modulation and Coding Scheme (MCS) of user i on SB j . Therefore, the use of $r_{i,j,k}^{UL}(t)$ also allows the proposed algorithm to take into consideration the variations in the link quality, since the MCS is determined based on the experienced channel conditions.

The proposed algorithm begins by sorting in descending order of $m_{i,k}^{UL}(t)$ the set of active users (RRC-connected), referred to as UE . Its aim is to prioritize users with higher MNO priority, ratio of estimated packet delay $d_{i,k}^{UL}(t)$ to the delay threshold $d_{th,i,k}$, high $\bar{D}_{i,k}^{UL}(t)$ and low $\bar{R}_{i,k}^{UL}(t)$, limited power transmission requirements in the uplink and increased data rate expectation per SB:

$$m_{i,k}^{UL}(t) = p_k \frac{d_{i,k}^{UL}(t)}{d_{th,i,k}} \exp\left(\frac{\bar{D}_{i,k}^{UL}(t)}{\bar{R}_{i,k}^{UL}(t)}\right) \times \frac{1}{P_{1,i,k} \cdot N_{RB,SB}} E[r_{i,j,k}^{UL}(t)]. \quad (6)$$

Then, the proposed algorithm performs as follows, see Fig. 1:

- 1) Firstly, determine whether a user actually needs an uplink transmission grant. A user is considered to need an uplink grant if he has sent a SR, i.e., $SR_{i,k}(t) = 1$, or if, based on his latest buffer status report (BSR), he has data expecting to be transmitted in the uplink, i.e., $BSR_{i,k}(t) > 0$. If the user does not currently require the allocation of any resources, he is removed from the set and the algorithm estimates the allocation needs of the next one.
- 2) If $SR_{i,k}(t) = 1$ or $BSR_{i,k}(t) > 0$, determine the set $K_{i,k}$, which consists of the available SBs that maximize the value of $m_{i,j,k}^{UL}(t)$, i.e., $K_{i,k} = \{j' \in \Phi : i = \arg \max_{i' \in UE} (m_{i',j',k'}^{UL}(t))\}$. The SBs of $K_{i,k}$ are not always contiguous.
- 3) If $K_{i,k}$ has more than one SBs, the SB j^* with the highest signal-to-noise ratio (SNR) $\gamma_{i,j,k}$ is found, i.e., $j^* = \arg \max_{j \in K_{i,k}} (\gamma_{i,j,k})$ and, if its bit error rate (BER), i.e., $BER_{i,j^*,k}$, does not exceed the threshold τ , the SB is included in set

Fig. 1: Flowchart of the proposed uplink spectrum sharing algorithm in each Time Transmission Interval (TTI).

$G_{i,k}$, i.e., the set of all SBs allocated to user i in this subframe.

- 4) Calculate the set $G_{i,k}$, which contains SB j^* , as well as the maximum number of contiguous SBs neighboring j^* that can be allocated to user i . A SB j is included in set $G_{i,k}$, if i) it is not already allocated to another user, i.e., $j \in \Phi$, ii) it maximizes $m_{i,j,k}^{UL}(t)$, i.e., $i = \arg \max_{i' \in UE} (m_{i',j,k}^{UL}(t))$, iii) it is adjacent to another SB that is already included in $G_{i,k}$, i.e., $\exists j' \in G_{i,k} : |j - j'| = 1$, iv) its BER value is lower than the threshold τ , and v) the included SBs cannot serve all the user's pending traffic. In order to determine the SBs of G_i , the algorithm starts from j^* and checks both directions for the possibility of expansion, i.e., SBs with $j < j^*$ and $j > j^*$. In each case, this process is terminated if a SB that does not meet at least one of the above constraints is found.

The performance complexity of the algorithm is

TABLE I: Simulation Parameters

Parameter	Value
Physical layer	Spectrum pool size: 10 MHz, Subframe length T_{sf} : 1 ms, Number of RBs (N_{RB}^{UL}): 50
RB format	Subcarriers per RB (N_{RB}^{RB}): 12, Symbols per RB (N_{RB}^{SC}): 7, Subcarrier spacing: 15 kHz
RS transmissions	2 transmissions per subframe
TDD configuration	Configuration 1, DL:UL 3:2
MCS	QPSK $1/2$, 16-QAM $1/2$, 64-QAM $3/4$
Path loss model	ITU-R UMi, UMa, NLOS [7]
Receiver antenna gain (BS)	5 dBi
Transmitter antenna gain	0 dBi
Thermal Noise Spectral Density	-174 dBm/Hz
UE Noise Figure	9 dBm
Control Channel Overhead	0 dB
Interference Margin	1 dB
Fading	Rayleigh
Shadowing	Log normal, $\sigma=4$ dB
Max UE transmission power	20 dBm
$P_{0,PUSCH}$	-57 dBm
Path loss compensation factor (α)	0.7
$d_{th,i}$	20 ms
RLC mode	Unacknowledged mode (UM)
Traffic model	H264 video QCIF 176×144
Protocol header sizes (RTP-CRC)	13 B
Moving average factor (β)	0.2
Inter-site distance	100 m
Antenna height (UE)	1.5 m
Antenna height (BS)	10 m
Average building height (h)	20 m
Street width (W)	20 m
Simulation time	67 s

linear in N_{SB} and $|UE|$, i.e., $O(|UE| \cdot N_{SB})$ [6].

IV. SIMULATION RESULTS

The performance of the proposed co-primary uplink spectrum sharing algorithm is evaluated through MATLAB simulations. The proposed system is compared to a legacy one that statically divides the shared resources based only on the MNOs' spectrum access priorities and allocates them to each MNO using the algorithm of [6]. Based on the proposed system model, the simulation environment considers an LTE cell, shared between two MNOs. An increasing number of UE devices is considered, each one with one uplink video connection. The performance indicators considered are the packet timeout rate, goodput, average delay, and fairness. The performance evaluation parameters are included in Table I. For the purpose of statistical accuracy, results have been averaged over 100 simulation runs.

Fig. 2 shows the average packet timeout rate, i.e., the number of packets that expire in the unit of time, being no longer useful at the receiver, versus the number of users per MNO and the shared spectrum access priority of MNO_1 , p_1 , for the systems that employ the proposed and static spectrum sharing algorithms.

(a) MNO_1

(b) MNO_2

Fig. 2: Average packet timeout rate w.r.t. the number of users and the shared spectrum access priority for (a) MNO_1 and (b) MNO_2 .

The priority of MNO_2 , is defined as $p_2 = 1 - p_1$. The total number of users N is in the range of $[5, 25]$, while the number of users of each MNO is defined as: $N_1 = \lfloor N/2 \rfloor$ and $N_2 = N - N_1$. For both MNOS the packet timeout rate increases with the number of users, since increasing the number of users results in higher congestion, which leads to longer queuing time and, eventually to more packet expirations. The effect of the shared spectrum priority, p_k , is also shown. The mean packet timeout rate of MNO_1 follows a declining course as p_1 increases, while the packet timeout rate of MNO_2 follows the opposite course. This is due to the proposed algorithm taking into consideration the shared spectrum access priority of each MNO during the resource allocation. The proposed co-primary spectrum sharing system reduces the packet timeout rate by 72% at most compared to the static sharing approach, since the latter divides the available resources based only on the MNOS' spectrum access priorities, without taking into consideration the real-time QoS status of the individual connections.

(a) MNO_1

(b) MNO_2

Fig. 3: Goodput w.r.t. the number of users and the shared spectrum access priority for (a) MNO_1 and (b) MNO_2 .

Fig. 3 depicts the average goodput of both MNOS. The goodput is defined as the rate of bits that are delivered to the application layer per unit of time. For both systems, the goodput decreases as the number of users increases, due to the increasing congestion, which results in unacceptable packet delays and timeouts. Moreover, the average goodput increases with the increase of the MNO priority. The proposed, QoS aware, spectrum sharing algorithm outperforms the static sharing system in terms of goodput by a factor of 2.3 at most.

Fig. 4 depicts the average packet delay versus the number of users and the shared spectrum access priority. In the proposed system, for both MNOS, the average packet delay follows a slightly increasing course with the number of users, due to the increased congestion and the need for longer queuing times. Moreover, the average delay slightly decreases with the increase of the shared spectrum priority of the MNO, due to the fact that the proposed algorithm favours users based on the priority of the MNO they are associated with. More-

(a) MNO_1

(b) MNO_2

Fig. 4: Average packet delay w.r.t. the number of users and the shared spectrum access priority for (a) MNO_1 and (b) MNO_2 .

over, the proposed and static systems have comparable average delay performance.

Fig. 5 depicts the fairness, using the Jain Index of Fairness, versus the number of users of both operators and the shared spectrum access priority. The fairness of the proposed system is considerably high, outperforming the static one by 46% at most, since the proposed algorithm favours users who have suffered from high average delay and low average data rate in their earlier allocations.

V. CONCLUSION

In this paper we proposed a co-primary spectrum sharing algorithm for LTE systems in the uplink, which considers the QoS requirements of real-time applications. The proposed algorithm complies with the realistic limitations of a localized SC-FDMA uplink system, i.e., no information on the uplink packet delays, limited information on the buffer status of the users, and need to allocate contiguous sets of RBs to each user. Emphasizing on the delay requirements of real-time applications,

Fig. 5: Fairness w.r.t. the number of users and the shared spectrum access priority.

users are prioritized based on an estimation of their packet delays, the average delay and data rate of earlier allocations, the required transmission power and the MNO spectrum priority. Simulation results highlighted the notable performance improvement achieved in terms of packet timeout rate, goodput, and fairness. Our future plans include the adaptation of the proposed algorithm in order to be applied to the downlink direction.

ACKNOWLEDGMENT

The research leading to these results received funding from the European Commission H2020 programme under grant agreement no 671705 (SPEED-5G project).

REFERENCES

- [1] T. Sanguanpuak, S. Guruacharya, N. Rajatheva and M. Latva-Aho, "Resource allocation for co-primary spectrum sharing in MIMO networks", in *Proc. IEEE International Conference on Communication Workshop (ICCW)*, 2015, pp.1083-1088.
- [2] S. Hailu, A.A. Dowhuszko and O. Tirkkonen, "Adaptive co-primary shared access between co-located radio access networks", in *Proc. 9th Int. Conf. on Cognitive Radio Oriented Wireless Networks and Communications (CROWNCOM)*, 2014, pp.131-135.
- [3] J. Lindblom and E.G. Larsson, "Does non-orthogonal spectrum sharing in the same cell improve the sum-rate of wireless operators?", in *Proc. IEEE 13th Int. Workshop on Signal Processing Advances in Wireless Commun. (SPAWC)*, 2012, pp.6-10.
- [4] R. Litjens, H. Zhang, I. Noppen, L. Yu, E. Karipidis and K. Borner, "System-Level Assessment of Non-Orthogonal Spectrum Sharing via Transmit Beamforming", in *Proc. IEEE 77th Conf. on Vehicular Technology Conference (VTC Spring)*, 2013, pp.1-6.
- [5] P. Luoto, M. Bennis, P. Pirinen, S. Samarakoon and M. Latva-aho, "Enhanced Co-Primary Spectrum Sharing Method for Multi-Operator Networks", in *IEEE Transactions on Mobile Computing*, vol.16, no.12, pp.3347-3360, Dec. 2017.
- [6] D. Triantafyllopoulou, K. Kollias and K. Moessner, "QoS and Energy Efficient Resource Allocation in Uplink SC-FDMA Systems", *IEEE Transactions on Wireless Communications*, vol.14, no.6, pp.3033-3045, June 2015.
- [7] 3GPP TR 36.814, V9.2.0 (2017-03): Further advancements for E-UTRA physical layer aspects (Release 9).