LOW-FEEDBACK COOPERATIVE OPPORTUNISTIC TRANSMISSION FOR DYNAMIC LICENSED SHARED ACCESS

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ABSTRACT

In order to meet the exponentially growing capacity demands of future mobile radio communication systems, the synergy of spectrum sharing methods, multi-antenna transmission schemes, small-cell offloading, and cooperative communication techniques is suggested. In this context, the mitigation of harmful interference, the provision of quality of service (QoS) guarantees, and the minimization of backhaul and channel state information (CSI) overhead are key challenges that have to be addressed. In this paper, we study the performance of a Licensed Shared Access (LSA) system comprised of a macro-cell sector (incumbent operator) and three partially overlapping small cells (licensee operator) placed within that sector. The small cells utilize a new low-feedback cooperative opportunistic beamforming (OBF) with proportional fair scheduling (PFS) transmission scheme to ensure that the proposed system is able to reach the mentioned goals above. Simulation results show that this system attains a substantial fraction of the available sum-rate capacity with minimal feedback.

***Index Terms*—** Licensed Shared Access (LSA), Quality of Service (QoS), Opportunistic Beamforming (OBF), Proportional Fair Scheduling (PFS), Channel State Information (CSI).

1. INTRODUCTION

Next-generation mobile radio communications systems should provide sufficiently high capacity to accommodate the expected enormous mobile data traffic growth [1]. However, the scarcity of the radio spectrum [2] prohibits mobile network operators (MNOs) from acquiring additional spectral resources in order to meet the capacity requirements of future mobile broadband (MBB) services. As a consequence, a number of complementary techniques has been suggested to address the spectrum crunch problem:

- Spectrum sharing improves the efficiency of spectrum utilization by enabling a secondary system (SS) to exploit "holes" in the licensed spectrum of a primary system (PS) in the frequency, time and space dimensions [4]. Still, traditional approaches based on cognitive radio (CR) technology cannot ensure the protection of the PS from harmful interference neither can they provide quality-of-service (QoS) guarantees to the users of the SS [5].
- Multiple-input multiple-output (MIMO) transmission schemes mitigate co-channel interference and increase the spectral efficiency through the exploitation of the spatial degrees of freedom (DoFs) provided by the use of multiple antennas at the transmitter (Tx) or / and receiver (Rx) [6]. On the other hand, though, they often result in high channel state information (CSI) feedback overhead.
- Cooperative MIMO transmission techniques, such as coordinated beamforming (CBF) and network MIMO, reduce or even eliminate inter-cell interference (ICI) by enabling different base stations (BSs) to cooperate. These methods, though, require the sharing of control information (scheduling or / and beamforming vectors, CSI etc.) and possibly of data between the cooperating nodes, thus placing an excessive burden on the mobile backhaul [7].
- Cell-densification, which is accomplished through the deployment of small cells, enhances frequency reuse. However, special care should be taken at the mitigation of co-tier and cross-tier interference in the resulting two-tier heterogeneous network (HetNet) [8].

There exist also alternatives that borrow elements from these methods that have the potential to address the issues associated with them:

Licensed Shared Access LSA is a recently proposed spectrum sharing paradigm [9] which overcomes the problems of CR-based methods by using a Spectrum Sharing Agreement between the LSA licensee and the incumbent. However, it would be desirable to enhance the dynamicity of spectrum access under the LSA framework, provided that such an advanced LSA system would be still able to meet the QoS requirements of both involved parties.

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Opportunistic Beamforming In this method, each BS chooses a beam in a pseudo-random fashion from a fixed predetermined set of beams; each mobile user (MU) feeds back only the signal-to-interference-plus-noise-ratio (SINR) that it "sees" with the current selection of beamforming weights; and then the BS applies proportional fair scheduling (PFS), thus selecting the user with the most favorable instantaneous channel quality (i.e., the one whose rate is near to its own peak, according to the service history). When the number of users is large, OBF performs almost optimal beamforming per-user despite the absence of CSI at the transmitter (CSIT) [10,11].

With the above in mind, in this paper we study a dynamic LSA system where three partially overlapping micro-cells belonging to the LSA licensee are placed within a sector of a macro-cell belonging to the incumbent. The LSA licensee is allowed to transmit simultaneously with the incumbent, provided that a predictable QoS level is ensured for the users of both of them. In order to accomplish this task as well as to limit the required communication / cooperation overhead, the small-cell BSs make use of OBF with PFS and follow a simple cooperation approach which simply consists of finding every time the optimum, in terms of the achieved sum-rate, n-tuple of small-cells ($n = 0, \dots, 3$) to transmit that does not cause intolerable interference to the users of the macro-cell BS or any of the small-cell BSs. The considered setup is illustrated in Fig. 1.

Numerical simulation results have shown that the proposed technique boosts the sum-rate performance of the SS while, at the same time, it does not degrade the performance of the PS.

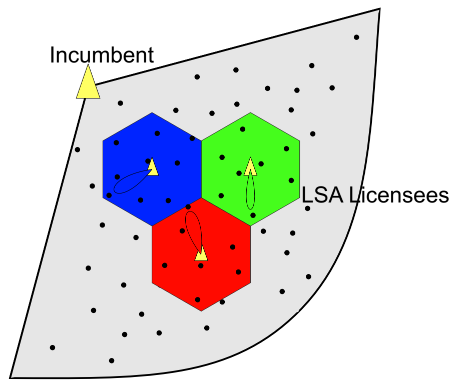

Fig. 1. System setup.

	Cooperation Between Secondary BSs
1.	All secondary BSs transmit simultaneously, if no PU or SU SINR threshold violations occur by these transmissions.
2.	Otherwise, the best pair of secondary BSs, in terms of the achieved sum-rate, transmits, provided that the PU and SU SINR thresholds are respected.
3.	Else, only one secondary BS from the previously selected pair transmits, given that it does not degrade the transmission of the PU below its predefined SINR threshold. The priority is given to the BS with the highest rate.
4.	If no combination / selection of secondary BSs can meet the given QoS requirements, then all of them remain idle and only the primary BS serves its selected user, with the SNR-based rate this time, since there is no interference.

Table 1. Cooperation scheme.

2. SYSTEM SETUP AND COOPERATION SCHEME

We adopt the notation BS_l ($l = 1, \dots, 4$) where $l = 1$ is used to denote the primary BS (incumbent) and $l = 2, \dots, 4$ is used for the secondary BSs (LSA licensee). Similarly, the transmit power of each BS and the corresponding cells are denoted as P_l and cell_l, respectively. The cell radius r_l is 7.5km for the macro-cell and 1.5km for the micro-cells.

All BSs are equipped with $N_t = 4$ antennas and wish to communicate with their respective primary user (PU) or secondary user (SU). Each MU makes use of a single-antenna user equipment (UE), i.e., $N_r = 1$. This is a realistic assumption, since in practice it is difficult to place multiple antennas at a UE due to cost, size, and power consumption constraints. Thus, a (4,1) Multiple-Input Single-Output (MISO) channel is formed between each BS and MU at the DL.

Each BS schedules a single user in each timeslot (TS). BS_1 makes use of PFS to select the PU, while $\text{BS}_2 - \text{BS}_4$ adopt OBF with PFS to schedule their SUs.

We assume a user population of $2K$ mobile users MU_k ($k = 1, \dots, 2K$), where K primary users PU_k ($k = 1, \dots, K$) are randomly placed in the sector of interest of cell_1 (and possibly within the coverage area of $\text{cell}_2 - \text{cell}_4$), while K secondary users SU_k ($k = K+1, \dots, 1K$) are randomly placed at $\text{cell}_2 - \text{cell}_4$.

We consider two different scenarios. In the baseline scenario, the secondary BSs transmit in a round-robin fashion. A PU SINR threshold γ_{Th}^{PU} is set and assumed to be available through the LSA repository. In any TS, the active secondary BS serves its preferred SU only if this potential transmission would not degrade the channel quality of the PU below the predefined PU SINR threshold. Otherwise, the secondary BS remains idle in this TS. Note that in each TS the secondary BSs choose a different random beam. Moreover, MUs feed their instantaneous SINRs back to the serving BSs.

In the second scenario, which is closest to the LSA spirit, a SU SINR threshold γ_{Th}^{SU} is also set. Secondary BSs cooperate in order to provide the best possible performance for both the incumbent and the LSA licensee, under the QoS constraints, by deciding in a slot-by-slot basis which of them will transmit (see Table 1).

3. COOPERATIVE TRANSMISSION AND SCHEDULING

3.1. Signal and Channel Models

Let $\mathbf{h}_{k,l} \in \mathbb{C}^{1\times N_t}$ ($k = 1, \ldots, 2K, l = 1, \ldots, 4$), with $\mathbb{C}$ denoting the set of complex numbers, be the channel gain vectors between MU_k and BS_l. A block fading channel model is assumed, such that $\mathbf{h}_{k,l}$ remain constant over TSs of duration T samples.

In Scenario 1, the baseband received signals in each TS are given by:

$$y_k^{PU}(t) = \underbrace{\sqrt{P_1}\mathbf{h}_{k,1}(t)x_1(t)}_{\substack{\text{desired signal}\\(l=1)}} + \underbrace{\sqrt{P_l}\mathbf{h}_{k,l}(t)x_l(t)}_{\substack{\text{interference}\\(l=2,\ldots,4)}} + \underbrace{n_k(t)}_{\text{noise}}. \quad (1)$$

$$y_k^{SU_l}(t) = \underbrace{\sqrt{P_l}\mathbf{h}_{k,l}(t)x_l(t)}_{\substack{\text{desired signal}\\(l=2,\ldots,4)}} + \underbrace{\sqrt{P_1}\mathbf{h}_{k,1}(t)x_1(t)}_{\substack{\text{interference}\\(l=1)}} + \underbrace{n_k(t)}_{\text{noise}}. \quad (2)$$

$x_l \in \mathbb{C}^{N_t\times T}$ ($l = 1, \ldots, 4$) are matrices containing the T transmitted symbols in TS t for BS_l and $n_k(t) \in \mathbb{C}^{1\times T}$ is zero-mean additive white Gaussian noise (ZM-AWGN) vector with covariance matrix $\sigma_k^2\mathbf{I}_T$, where $\mathbf{I}_T$ is the $T \times T$ identity matrix.

Note that when the corresponding secondary BS is not allowed to transmit due to QoS constraints, then the baseband received signal at PU_k is given by

$$y_k^{PU}(t) = \underbrace{\sqrt{P_1}\mathbf{h}_{k,1}(t)x_1(t)}_{\substack{\text{desired signal}\\(l=1)}} + \underbrace{n_k(t)}_{\text{noise}}. \quad (3)$$

In Scenario 2, when all the secondary BSs transmit, the baseband received signal at PU_k is

$$y_k^{PU}(t) = \underbrace{\sqrt{P_1}\mathbf{h}_{k,1}(t)x_1(t)}_{\substack{\text{desired signal}\\(l=1)}} + \sum_{l=2}^{4}\underbrace{\sqrt{P_l}\mathbf{h}_{k,l}(t)x_l(t)}_{\substack{\text{interference}\\(l=2,\ldots,4)}} + \underbrace{n_k(t)}_{\text{noise}}, \quad (4)$$

while the baseband received signal at the scheduled SU served by BS_l ($l \neq 1$), $\text{SU}_{k,l}$, is given by

$$y_k^{SU_l}(t) = \underbrace{\sqrt{P_l}\mathbf{h}_{k,l}(t)x_l(t)}_{\substack{\text{desired signal}\\(l=2,\ldots,4)}} + \underbrace{\sqrt{P_j}\mathbf{h}_{k,j}(t)x_j(t)}_{\substack{\text{interference}\\(j=1,\ldots,4,j\neq l)}} + \underbrace{n_k(t)}_{\text{noise}}. \quad (5)$$

Similar relations hold when two secondary BSs transmit, while when only one secondary BS schedules a SU or all secondary BSs remain idle, the corresponding equations reduce to (1)–(3).

The elements of $\mathbf{h}_{k,l}$ are assumed to be independent zero-mean complex Gaussian random variables (RVs) with variance [2]

$$a_{k,l}^2 = \underbrace{PL_{\text{ref}^l}\left(\frac{d_{k,l}}{d_{\text{ref}}^l}\right)^{-\Gamma}}_{\text{Path Loss}} \cdot \underbrace{s_{k,l}}_{\text{Shadowing}} \cdot \underbrace{g_{k,l}}_{\substack{\text{Normalized}\\\text{direction-based}\\\text{antenna response}}}, \quad (6)$$

where PL_{ref^l} is the path loss at some reference distance from BS_l with $d_{\text{ref}^l} = 1\text{km}$ for $l = 1$ and $d_{\text{ref}^l} = 100\text{m}$ otherwise, $d_{k,l}$ is the distance between MU_k and BS_l, Γ is the path loss exponent expressed by

$$\Gamma = \begin{cases} 0 & d_{k,l} < 30\text{m} \\ 2 & 30\text{m} \leq d_{k,l} \leq d_{\text{ref}}^l \\ 3.7 & d_{k,l} > d_{\text{ref}}^l \end{cases}, \quad (7)$$

$s_{k,l} = 10^{\sigma_s/10}$ is a log-normal RV which represents shadow fading with standard deviation $\sigma_s = 8\text{dB}$, and $g_{k,l}$ is the normalized direction-based antenna response of BS_l. For the primary BS ($l = 1$), we have $g_{k,l} = 1\text{dB}$, while for the secondary BSs, assuming a parabolic response model, $g_{k,l}$ is given in dB by

$$g_{k,l}(\theta_{k,l} - \omega_l) = \max\left\{-12\left(\frac{\theta_{k,l} - \omega_l}{\Theta}\right)^2, A_s\right\}. \quad (8)$$

In (8), $\theta_{k,l}$ is the direction of MU_k with respect to the location of BS_l, ω_l is the beam direction of BS_l, $\Theta = 70\pi/180$ is the 3-dB beamwidth of the response, and $A_s = -20\text{dB}$ is the sidelobe level of the response.

3.2. Joint OBF and PFS

In each TS, each secondary BS_l ($l = 2, \ldots, 4$) transmits independently from the others its own pilot signal by selecting a beam in a pseudo-random manner from the fixed predetermined set of beams, as in the case of transmitting a data signal. Then, each mobile user MU_k estimates $\mathbf{h}_{k,l}$ and feeds its estimated SINR $\gamma_k(t)$ back to its corresponding BS_l or, equivalently, its "requested" data rate $R_k(t)$ (i.e., the maximum data rate that the channel can currently support), which is given by Shannon's capacity formula

$$R_k(t) = \log_2\left[1 + \gamma_k(t)\right]. \quad (9)$$

The BS scheduler keeps track of the average throughput of each user $T_k(t)$ over a sliding window of the past with length W TSs and schedules the user MU_k with the largest ratio $R_k(t)/T_k(t)$. The BS updates the average throughputs in each TS according to the following formula:

$$T_k(t+1) = \begin{cases} \left(1 - \frac{1}{W}\right)T_k(t) + \frac{R_k(t)}{W}, & k = k^* \\ \left(1 - \frac{1}{W}\right)T_k(t) & k \neq k^* \end{cases}. \quad (10)$$

In Scenario 1, SINRs are given by

$$\gamma_k^{\mathrm{PU}}(t) = \frac{P_1\|\mathbf{h}_{k,l}(t)\|^2}{P_l\|\mathbf{h}_{k,l}(t)\|^2 + \sigma_k^2},\ \ l = 2,\ldots,4. \quad (11)$$

$$\gamma_k^{\mathrm{SU}_l}(t) = \frac{P_l\|\mathbf{h}_{k,l}(t)\|^2}{P_1\|\mathbf{h}_{k,l}(t)\|^2 + \sigma_k^2},\ \ l = 2,\ldots,4. \quad (12)$$

If $\gamma_k^{\mathrm{PU}} < \gamma_{Th}^{\mathrm{PU}}$, the active secondary BS in the TS of interest remains idle and the SINR in (11) becomes the SNR given by

$$\gamma_k^{\mathrm{PU}}(t) = \frac{P_1\|\mathbf{h}_{k,l}(t)\|^2}{\sigma_k^2}. \quad (13)$$

In Scenario 2, assuming that all secondary BSs transmit simultaneously, we have

$$\gamma_k^{\mathrm{PU}}(t) = \frac{P_1\|\mathbf{h}_{k,l}(t)\|^2}{\sum\limits_{l=2}^{4} P_l\|\mathbf{h}_{k,l}(t)\|^2 + \sigma_k^2}. \quad (14)$$

$$\gamma_k^{\mathrm{SU}_l}(t) = \frac{P_l\|\mathbf{h}_{k,l}(t)\|^2}{\sum\limits_{\substack{j=1\\ j\neq l}}^{4} P_j\|\mathbf{h}_{k,j}(t)\|^2 + \sigma_k^2},\ \ l = 2,\ldots,4. \quad (15)$$

If $\gamma_k^{\mathrm{PU}} < \gamma_{Th}^{\mathrm{PU}}$ or / and $\gamma_k^{\mathrm{SU}_l} < \gamma_{Th}^{\mathrm{SU}_l}$, then the optimum pair of secondary BSs, in terms of the sum-rate $R_k(t)$, that does not degrade the QoS of the PU or the corresponding SUs will continue to transmit. If such a pair does not exist, then the secondary BS that does not affect the PU will serve its user, with priority given to the one with the maximum rate. Finally, if the PU SINR threshold is violated in any case, then all secondary BSs will remain idle.

The sum-rate of the SS in each TS in Scenario 2 is given by

$$R_k^{SS}(t) = \sum_{l=2}^{4} \log_2\left[1 + \gamma_k^{SU_l}(t)\right]. \quad (16)$$

4. PERFORMANCE RESULTS

In this section, we present the performance results of the proposed system, as evaluated by numerical simulations. The considered performance metric is the average throughput of the PS and the SS. These values are compared with the throughputs obtained for the PS (SS) when the SS (PS) is inactive, and assuming that still the rules defined in each scenario hold for the SS. For the isolated PS case (i.e., when the SS is idle), the received baseband signal and the SNR are given by (3) and (13), respectively. In the case of isolated SS, then under the context of Scenario 1 the received baseband signal and the SNR are given by (2) and (12), respectively, by setting $P_1 = 0$. In Scenario 2 (i.e., interference channel), the received baseband signal and the SINR are obtained from (5) and (15), respectively, by setting $P_1 = 0$.

Moreover, an upper bound for the performance of the system is used for comparison. More specifically, in this case that we call Scenario 3, the coexisting small cells are isolated from each other such that they form three orthogonal (i.e., non-interfering) (4,1) Multiple Input Single Output (MISO) channels with their selected users. The secondary BSs transmit simultaneously. Since we use the performance of this system as a benchmark, we do not consider any PU or SU SINR thresholds that would lead to a decision-making process that might force the SS to not allow all three secondary BSs to transmit simultaneously. In the absence of the macro-cell interferer, it is well known that, due to its orthogonality, this setup is the optimum one when each BS schedules only a single user in each TS. With the PS present, it is still optimum because in the capacity regime all signals, including the one transmitted from the incumbent, are Gaussian. Thus, this setup is essentially the same as the one with the incumbent absent (but with worse SINR due to the interference caused by the PS). In the presence of the incumbent, the received baseband signal of the PU and the corresponding SINR are given in this case by (4) and (14), respectively. Similarly, for the SUs the equations (2) and (12) apply. If the PS is inactive, then we have to set $P_1 = 0$ in the last two equations. In any case, the rate of the SS is given by (16). In terms of sum-rate, Scenario 1 and Scenario 3 correspond to the two extreme cases which bound the performance of the proposed cooperation scheme. It is easy to verify that $R_{\perp} = 3R_{rr}$, where $R_{\perp}$ and R_{rr} are the sum-rates of the SS in Scenario 3 and 1, respectively.

Performance results are obtained over 1,000 simulation runs with an increasing number of users $2K = 8, 16, 32, 64, 128$; transmit powers $P_1 = 15$W for the macro-cell BS and $P_l = 1$W ($l = 2,\ldots,4$) for the micro-cell BSs; PFS window size $W = 100$ TSs for both systems; and values of 0dB or 1dB for the PU and SU SINR thresholds, γ_{Th}^{PU} and γ_{Th}^{SU}, respectively. Note that the setting of the appropriate values for the SINR thresholds depends on multiple factors, such as the transmit power and noise power level, the geometry of the considered setup, the severity of fading etc. We have focused on the low SINR values regime, which not only suits the transmission profile of the considered system but also reflects closer the reality.

Fig. 2-5 show the average throughputs of the considered use cases versus the size of the user population. We note that this simple, minimal cooperation scheme lies between the two extreme cases of Round-Robin and Orthogonal setups in terms of average throughput (usually above the half-way point) while causing only a slight degradation to the performance of the PS. Moreover, this low-feedback cooperation technique performs better than the Round-Robin system even when the latter is isolated (i.e., the PS is idle). Furthermore, it is apparent that this method exploits multi-user diversity. Finally, we see that as the value

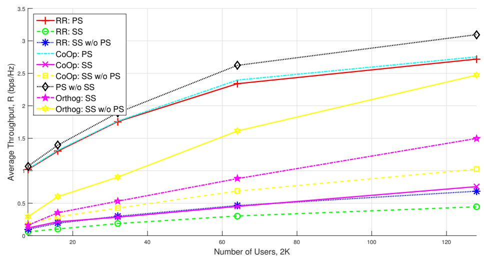

Fig. 2. Average throughput for $\gamma_{Th}^{PU} = \gamma_{Th}^{SU} = 0$dB.

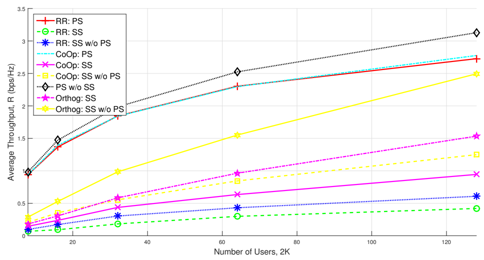

Fig. 3. Average throughput for $\gamma_{Th}^{PU} = 0$dB, $\gamma_{Th}^{SU} = 1$dB.

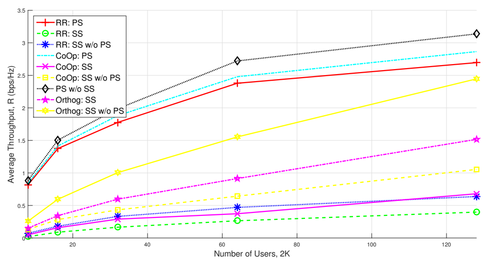

Fig. 4. Average throughput for $\gamma_{Th}^{PU} = 1$dB, $\gamma_{Th}^{SU} = 0$dB.

of the SINR thresholds increases, the performance of the SS in the relevant scenarios becomes worse, since then SINR threshold violations occur more often and, therefore, some secondary BS transmissions might be blocked.

5. CONCLUSIONS AND FUTURE WORK

In this paper, a simple BS cooperation scheme was studied in the context of a dynamic LSA system. Numerical simulation results have indicated that this technique provides significant performance gains while requiring only minimal feedback. In the future, we plan to extend this setup to arbitrary numbers of licensee cells and multi-user transmission.

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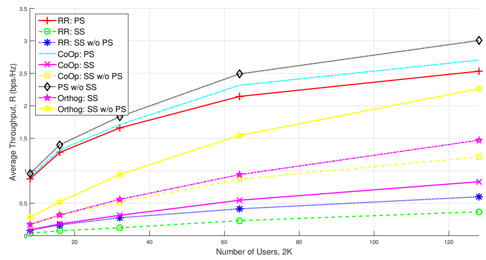

Fig. 5. Average throughput for $\gamma_{Th}^{PU} = \gamma_{Th}^{SU} = 1$dB.