Transmission Strategy for Interference Alignment in a System-level Perspective

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***Abstract*—The paper builds up on the idea of separating, in the time dimension, between conventional uncoordinated MIMO and IA transmission. The former usually utilizes all available dimensions (antennas) to send useful information, while the latter mitigates inter-cell interference. Due to the multitude of users in cellular networks, the transmission schemes are suitable for different groups of users. Therefore, in order to take advantage of both schemes, the users are classified into two groups: one with those users that supposedly benefit from cooperation and the other with those that should not cooperate. The proposed method for grouping the users has the advantage of being based on a simple decision metric, which avoids having to calculate precoders for all different possible combinations. Since each group must apply the proper transmission scheme, a fraction of the temporal resources is dedicated to each type of transmission. An automatic reservation of the temporal resources and an adaptive adjustment of the grouping threshold for each user, which avoids having to empirically determine a single threshold, are also proposed. These proposed mechanisms are shown to provide performance gains of up to 30% over the conventional transmissions.**

***Index Terms*—Interference alignment. Coordinated Multi-Point System. System-level.**

I. Introduction

Mitigating interference is a recurring issue present since the origin of cellular networks. Interference Alignment (IA) has been recently seen as a promising approach to handle the interference in wireless networks, at least for well-controlled scenarios [1].

The IA technique exploits the cooperation among the transmitter and receiver pairs to design precoders that align the interference in each receiver onto a subspace smaller than the number of interferers [2]. Afterwards, the desired signals can be decoded free-of-interference. The concept behind IA is very general in the sense that the signals can be properly aligned in any dimension, including time, frequency, or space. Several algorithms relying on this concept have already been published, some more altruistic, others less, in the sense of completely aligning the interference or seeking other goals [3]–[5]. In this paper we focus on IA applied along the spatial domain.

From the brief explanation of the IA concept, it is clear that the technique sacrifices some dimensions to mitigate the interference. Therefore, given the plurality of users in cellular networks, not all of them would benefit from interference mitigation. For instance, users with very good channel conditions and perceiving low interference would rather send useful information in all available dimensions. Hence, in practical cellular networks IA might be worthwhile just for some users.

In this work, we present the concept of Coordinated Multi-Point (CoMP)-gain that tries to express how much IA can improve the Signal to Interference-plus-Noise Ratio (SINR) perceived by the users. Based on a CoMP-gain threshold, we classify the users as users supposedly benefiting from the cooperation and users that should not cooperate. Once these two groups of users are formed, we proportionally divide the temporal resources for transmissions inside each group. This may guarantee that each user will apply the most suitable transmission scheme. Therefore, we can expect a system performance improvement if we compare to networks applying only IA or only conventional transmissions. This strategy we denote by CoMP-gain-aware transmissions. The authors in [6], for example, have analyzed inter-cell interference techniques together with user selection algorithms, but without separating the users into different groups according to transmission technique.

Alternatively, we could calculate the IA and conventional precoders for all users to assure which transmission scheme would provide the best performance. However, calculating such an extensive amount of precoders may extremely increase the computational complexity. This makes the proposed transmission scheme even more appealing, since the CoMP-gain metric is very simple to calculate.

In the current paper, we also try to improve IA transmission by pursuing the automation of the steps related to the classification of users and threshold selection. The rest of the paper is divided as follows. Section II presents the system level models highlighting the enhancements on the CoMP-gain-aware transmission strategies. In section III, we present the computer simulation conditions and discuss some results. Finally, in section IV, we draw some conclusions.

II. System Model

A model has been designed to conduct the evaluations of the incorporation of IA mechanisms over a CoMP framework in a consistent manner, composed of many geographically distributed Transmission Points (TPs) connected through a fast backhaul to a Central Processing Unit (CPU).

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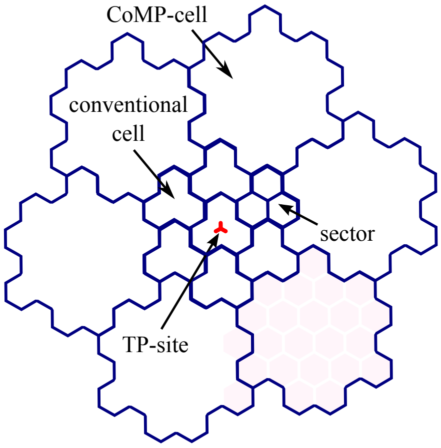

Fig. 1. Multicell scenario with seven CoMP-cells.

This system model comprises seven CoMP-cells, each with 21 TPs serving the User Equipments (UEs). These TPs are regularly distributed along the CoMP sectors as illustrated in Figure 1, considering an antenna radiation pattern with a 120^o beamwidth [7]. Each sector is modeled as a hexagon, whose maximum diameter is 334 m, which was chosen to simulate an urban scenario. In addition, a wrap-around approach is employed to avoid border effects. Although the system model is described in a more general manner, the simulations here were carried out with both UEs and TPs equipped with two co-located antennas.

We focus just on the downlink of this system, which employs Orthogonal Frequency Division Multiple Access (OFDMA) with equal power allocated among the sub-carriers. The sub-carriers are separated by 15 kHz and grouped in blocks of 12 adjacent sub-carriers as Physical Resource Blocks (PRBs) [8]. Each PRB can be assigned to one or more $\langle$TP, UE$\rangle$ pairs within each CoMP-cell, with six PRBs being considered in the simulations.

The channel coherence bandwidth is assumed larger than the PRB bandwidth. Regarding the 3rd Generation Partnership Project (3GPP) specifications [7] of fading environments, lower spatial correlation is observed since the TP antennas are all about the same height in the microcell [9].

The distance dependent Non Line of Sight (NLOS) pathloss in the microcell environment is based on the COST231 Walfish-Ikegami NLOS model. The pathloss for the urban micro environment is given by $PL = 35.7 + 38\log_{10}(\text{distance})$.

Regarding the antenna radiation pattern, 3GPP adopted the horizontal-only antenna radiation pattern as the standard configuration, which is given in dB as $G^{(a)}(\theta) = -\min\left\{12\left(\theta/70\right)^2, 20\right\}$, where θ is the azimuth in degrees [7].

Slow channel variations due to shadowing are modeled by a log-normal distribution of zero mean and standard deviation of 8 dB, and we assume that the shadowing among different UEs is equal within a same cell. Concerning the small-scale fading component, we assume the Spatial Channel Model (SCM), which is a stochastic channel model developed by 3GPP for evaluating Multiple Input Multiple Output (MIMO) system performance. SCM comprises relevant parameters such as phases, delays, Doppler frequency, and ray angles [7].

The transmit power per PRB for each TP is determined to assure that a given UE at the edge of the conventional cell should perceive the minimal Signal to Noise Ratio (SNR) required for achieving the lowest Modulation and Coding Scheme (MCS) without spatial precoding. This transmit power can be obtained from the link budget, at the beginning phase of the simulation.

We are abstracting the link-level functionalities through output metrics properly arranged such as Block Error Rate (BLER) $\times$ SNR curves obtained from [10]. By resorting to the Gaussian approximation for the total received interference, these link-level models are employed not only for obtaining the probability of failure of a given transmission, but also for executing the link adaptation mechanisms. The link adaptation searches for the modulation scheme that yields the maximum average throughput, $\bar{\text{r}}(\gamma, \text{MCS})$, under the current SINR value, γ, for each PRB independently.

$$\text{MCS index}^\star = \underset{\text{MCS index}}{\arg\max}\,\{\bar{\text{r}}(\gamma, \text{MCS index})\} \quad (1)$$

The SINR measured for a given link and PRB is taken into account to determine the BLER for the data block supposedly sent. The SINR $\gamma_{j,s}$ of the sth stream of UE j, on a given PRB and CoMP-cell, whose indexes are omitted, can be expressed as

$$\gamma_{j,s} = \frac{\left|\mathbf{u}_{j,s}^H \sum_{m=1}^{M} \mathbf{H}_{j,m}\mathbf{v}_{m,j,s}\right|^2}{\left|I_{j,s}\right|^2 + \sigma_n^2 \mathbf{u}_{j,s}^H \mathbf{u}_{j,s}}, \quad (2)$$

where $\mathbf{H}_{j,m}$ is the matrix $N_{RX} \times N_{TX}$ with complex channel coefficients from TP m to UE j; $\mathbf{v}_{m,j,s}$ is the vector of length N_{TX} representing the precoder in TP m related to stream s of UE j; $\mathbf{u}_{j,s}$ is the vector of length N_{RX} representing the receive filter related to stream s of UE j; σ_n^2 is the thermal noise power. The interference term $I_{j,s}$ is given by:

$$\begin{aligned} I_{j,s} = &\sum_{j'=1; j' \neq j}^{J} \sum_{s'=1}^{S} \mathbf{u}_{j,s}^H \sum_{m=1}^{M} \mathbf{H}_{j,m}\mathbf{v}_{m,j',s'} + \\ &\sum_{s'=1; s' \neq s}^{S} \mathbf{u}_{j,s}^H \sum_{m=1}^{M} \mathbf{H}_{j,m}\mathbf{v}_{m,j,s'}. \end{aligned} \quad (3)$$

We adapt the MCS for each PRB independently, but simultaneously for all intended TPs. Aligned with Long Term Evolution (LTE), a set of fifteen MCSs is available, each composed by a combination of modulation schemes — namely 4-, 16- and 64-Quadrature Amplitude Modulation (QAM) — and coding rates between 1/13 and 1. UEs with SINR value below -6.2 dB should not detect/decode the data block sent, because the BLER is expected to be greater than 1% even for the MCS with the lowest index. For the sake of simplicity, both transmission failure prediction and link adaptation functionalities are executed based on the exact measurements of inter and intra-CoMP-cell interference.

Depending on the system load, it may occur that not all users can be serviced at the same time. A random scheduler is thus adopted for selecting which users will be active during a certain period. The next subsection presents the transmission schemes for the UEs already selected.

A. Basic Transmission Strategies

1) Conventional: The simplest transmission strategy herein investigated is a strategy commonly referred to as *conventional*. The conventional transmission strategy assumes no coordination among TPs; each sector chooses one of its UEs and, thereby, the associated TP transmits to it. Hence, all available dimensions (antennas) can be used to send useful information and each TP is able to send two streams to its intended UE. The interference between the two streams of a same UE is dealt through Minimum Mean Square Error (MMSE) processing [11]: $\mathbf{V}_m = \tilde{\mathbf{H}}_{jm}^H \left(\tilde{\mathbf{H}}_{jm} \tilde{\mathbf{H}}_{jm}^H + \mathbf{\Psi}_{jm} \right)^{-1}$, where j is the index of the UE scheduled by TP m; the $\mathbf{\Psi}_{jm}$ matrix is given by $\mathbf{\Psi}_{jm} = \frac{\sigma_n^2}{P_{\text{PRB}}} \mathbf{I}$, where P_{PRB} is the transmission power per cell, whose maximum value is a constraint for power allocation.

2) Interference Alignment: Since UEs and TPs are equipped with two co-located antennas, IA is able to mitigate interference just among three TP-UE pairs, in accordance with IA feasibility conditions [12]. Therefore, compositions of three sectors associated with each TP-site must be created, leading to several independent IA transmissions being performed in the network.

Still according to the feasibility conditions, IA is able to send just one stream free-of-interference per pair. On the other hand, the conventional scheme allows the TPs to send two streams, since the transmission scheme uses all available dimensions. With these two transmission strategies, we clearly have a trade-off between sending more streams or having more reliable transmissions.

Due to its previously verified good performance, we focus our further analysis on IA with the MMSE criterion [5].

B. CoMP-gain-aware Transmission Strategies

The basic transmission strategies are redesigned to take advantage of the CoMP gain. Let us define *Geometry* (Ge) and *CoMP Geometry* (cGe) metrics for UE j, respectively, as:

$$Ge_j = \frac{p_{j,m(j)}}{\sum\limits_{\forall k: k \neq m(j)} p_{j,k} + \sigma_n^2}, \tag{4}$$

and

$$cGe_j = \frac{p_{j,m(j)}}{\sum\limits_{\forall k: c(k) \neq c(m(j))} p_{j,k} + \sigma_n^2}, \tag{5}$$

where $p_{j,m}$ gives the received power for UE j transmitted from TP m; $m(j)$ is a function that gives the serving TP m for UE j; and $c(m)$ gives the cluster index to which sector m belongs. The Geometry is related to the SINR perceived by a UE while the CoMP Geometry is related to the SINR the UE would perceive by mitigating the interference inside the cluster. Therefore, the metrics are connected with conventional and IA transmissions, respectively.

The CoMP Gain for UE j can thus be defined as:

$$\text{CoMP Gain}_j = \frac{cGe_j}{Ge_j}. \tag{6}$$

We are then able to specify the use of cooperation to only those users who present high potential to benefit from IA transmission and save resources for the other ones. This way, users are separated into two groups depending on whether they are supposed to take benefit from the cooperation or not.

The CoMP gain is the metric taken into account for such a decision, but there are several ways to do so. We can adopt a single threshold to define the users of the two aforementioned groups. Basically we compute the CoMP gain for every user in the CoMP-cell and compare all these measures with a threshold value: users whose CoMP gain is greater than this threshold are inserted into the High CoMP-gain Group (HG) and the other users into the Low CoMP-gain Group (LG).

All the TPs within a CoMP-cell can be assigned to transmit to HG users, then defining the *cooperating transmission*. Similarly, all the TPs within a CoMP-cell can be dedicated to transmit to LG users, defining the *non-cooperating transmission*. It is imperative that cooperating and non-cooperating transmission be separated to each other in the time resources. Each Transmission Time Interval (TTI) lasts 1 ms and is built up by 14 symbols. We must reserve part of the TTIs for the cooperating transmission and the remaining TTIs for the non-cooperating transmission.

By observing that a certain threshold value led to a certain proportion between HG and LG groups, we set the amounts of cooperating and non-cooperating TTIs to reflect similar proportion. A drawback of this approach is that it requires a test simulation to ascertain such distribution.

At least two important exceptions must be accounted for: (i) if there is no representative UE of HG in a particular sector, the associated TP will be dedicated to conventional transmissions; (ii) if there is no representative UE of LG in a particular sector, the HG UEs might also be scheduled for conventional transmissions.

1) Automatic TTI reservation: Instead of a fixed TTI reservation, as previously mentioned, we can also opt for an automatic mechanism for the reservation of TTIs. A simple way of implementing this automation is based on the current sampling distribution of users along the two CoMP-gain-based groups. This way, the proportion between cooperating and non-cooperating TTIs is established during execution time and it can be updated frequently.

Let us denote by N_c the number of consecutive cooperating TTIs and by N_n the number of consecutive non-cooperating TTIs. Then, after N_c TTIs of cooperating transmission, it is switched to non-cooperating, and after N_n additional TTIs, the transmission is switched back to the cooperating one; this alternation occurs periodically with $N_T = N_c + N_n$ being its cycle length.

We must previously determine a constant representing the maximum acceptable value for the N_T cycle. Then, considering the TTI as an indivisible resource in the Radio Resource Management (RRM) context, it is possible to automatically approximate the amount of TTIs among N_T to service the LG and the HG users. The longer the cycle N_T, the better the granularity available to such an approximation, but lower the ability to adapt to changes in the environment.

Whenever a cycle N_T is completed, N_c and N_n can be recomputed. In order to better track channel and interference variations, it is desirable to minimize N_T. Therefore, each subcarrier and CoMP-cell will have their own N_c, N_n and N_T values.

2) Adaptive per-UE threshold: We can also devise an alternative approach to avoid choosing a single threshold to the values of the CoMP gain. If we have multiple TPs serving multiple UEs we can choose whether the transmission is performed cooperatively or not. At this point, it is worth noticing that just the cooperating transmission is restricted to a single stream. If we keep the same transmission power, the receiver SNR per stream will be degraded as the number of streams, S, increases. This way, we can decide whether the transmission shall be cooperative or not by means of a simple inequality comparing the different estimates of channel capacity for each UE j:

$$\log_2 (1 + cGe_j) \underset{\text{Non-cooperation}}{\overset{\text{Cooperation}}{\gtrless}} S \log_2 \left(1 + \frac{Ge_j}{S}\right). \quad (7)$$

For the special case in which $S = 2$, the decision UE-by-UE can be simplified as:

$$\text{CoMP Gain}_j \underset{\text{Non-cooperation}}{\overset{\text{Cooperation}}{\gtrless}} 1 + \frac{Ge_j}{4}. \quad (8)$$

Therefore, many individual decisions on coordination or not will be taken in place of empirically choosing a single threshold to drive such a decision.

By adapting the threshold user-by-user, we have no other parameter indicating the cardinality of the LG group. Thus, the non-automatic TTI reservation is no longer acceptable. The reservation approach described in section II-B1 should be used instead.

III. Computer simulations

The simulation events are organized in snapshots, during which path loss and shadowing are assumed to remain constant for all links, while the temporal variations of fast fading are considered.

The evaluation of system level performance was carried out by means of *throughput* measures, which are taken along the snapshot lifetime. In order to capture the impact of long-term propagation effects on the system performance, eight snapshots are simulated, obtaining the performance metric estimates with confidence interval at a 90% level, based on Student's t-distribution. Herein offered load means the number of UEs physically present in a sector, regardless of whether they are scheduled or not; the larger the offered load, the smaller the throughput averaged over all UEs. Only the random scheduler approach is considered in the simulations.

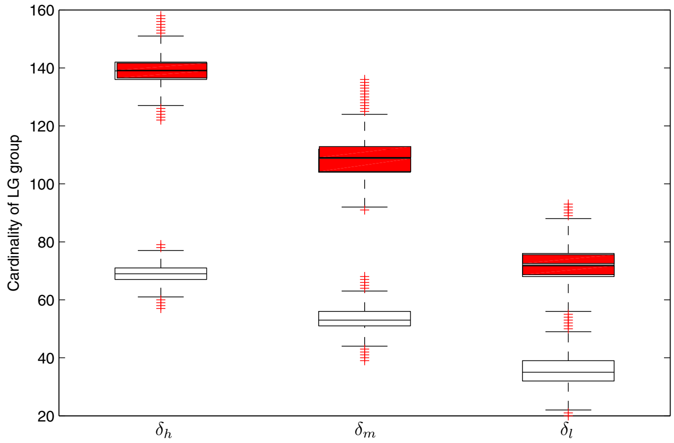

Fig. 2. Box-plot of the LG group cardinality for thresholds of δ_h, δ_m, and δ_l. The white boxes correspond to the system load of 4 UEs per sector, whereas red boxes correspond to 8 UEs per sector.

A. Results

Let us consider three different threshold values, say 1.067, 1.467, and 4.863, hereafter respectively referred to as δ_l, δ_m, and δ_h. These values were empirically found such that a (roughly) given percentage of users belong to the LG group. This is the exact percentage of consecutive TTIs reserved for non-cooperating transmission: for the threshold equal to δ_h, about 75% of users present low CoMP-gain, and then three consecutive TTIs are reserved for non-cooperating transmission and another one for cooperating transmission, which we may in short denote by (75%, 3, 1); for the δ_m threshold we have (50%, 1, 1), and for the δ_l threshold we have (25%, 1, 3). However, such percentages of LG UEs are merely expected in the average; the sample values can deviate significantly from these as observed in the following results.

In order to check the effect of setting such thresholds, we evaluate the cardinality of the LG group under each of those thresholds through a simulation campaign. Figure 2 shows the observed cardinalities of the LG group as a box plot gathering ten independent $1,000$-TTI simulations, for the threshold values of δ_h, δ_m, and δ_l and the system loads of 4 and 8 UEs per sector. Given a system load, we can note that changing the threshold value actually changes the proportion of LG UEs but not in the exact proportions expected. The proportions here are calculated considering the total amount of UEs present in a CoMP-cell, which gives 84 and 168 in case of 4 and 8 UEs per sector, respectively. For example, if we take the medians as the central measure, we obtain the proportions of 82%, 63%, and 42%, respectively for δ_h, δ_m, and δ_l, at simulations of 4 UEs per sector; at simulations of 8 UEs per sector, the corresponding proportions are 82%, 65% and 43%. Those results corroborate that the initially found values of 75%, 50%, and 25% may represent a sample proportion of LG users, but they are not representative as a central measure.

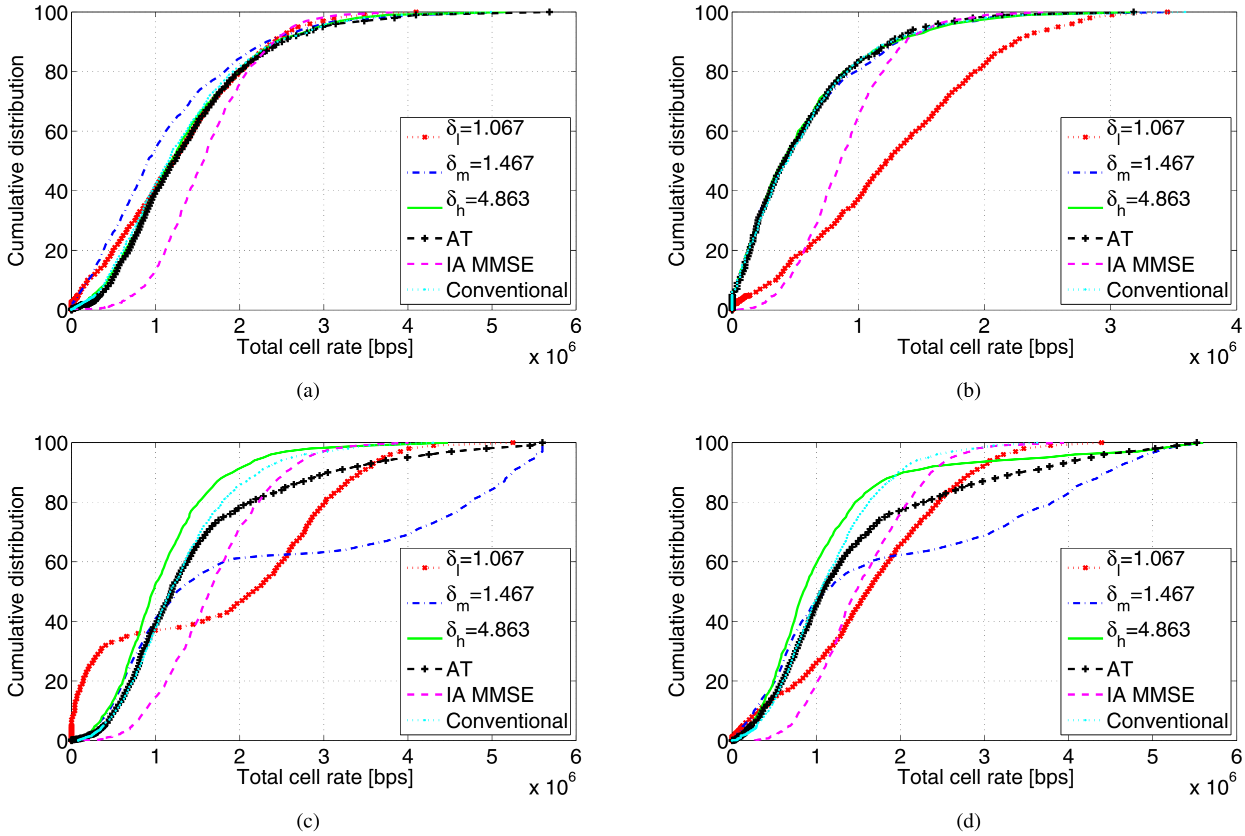

Fig. 3. Cumulative distribution of the total CoMP cell instant throughput under different CoMP-gain threshold configurations at loads of (a) 2, (b) 4, (c) 8 and (d) 10 UEs per sector.

For this reason, a dynamic approach may be preferred.

We can analyze the data regarding the amount of bits successfully transmitted in order to interpret the effectiveness of the transmission scheme. As follows, we observe the cumulative distribution of the total CoMP cell instant throughput in Figure 3. The curves are obtained for loads of 2, 4, 8, and 10 UEs per sector. For each load, the three aforementioned CoMP-gain threshold values are evaluated as well as the Adaptive per-UE Threshold (AT) approach. Except for the lowest load, where the multiuser diversity is not representative, the δ_l configuration provided better 90th percentile than for δ_h, due to the highest amount of candidate users for cooperation. However, the δ_m configuration provided the best 90th percentiles for high loads, indicating that the overload of either LG or HG group did not boost the performance of their subjects. In contrast, the δ_h configuration provided significantly higher 10th percentile than the δ_l; for example at eight users per sector, δ_h provided 420.0 kbps, while δ_l provided 39.4 kbps. It should be noticed that the performance is very sensitive to the threshold choice and the conditions of the multiple links. In this context, the AT approach plays an important role, since it provides good 10th and 90th performances without requiring such an empirical choice. At eight users per sector, for example, the AT approach provided the highest 10th percentile (519.6 kbps, against 39.4 kbps for δ_l) and the third 90th percentile. Finally, note that the best performance for the 10th percentile is achieved when we set the threshold to zero, which results just on IA MMSE transmissions. On the other hand, for the most favorable UEs the proposed scheme guarantees higher rates than both traditional transmissions schemes.

We have also analyzed the mean throughput for the different threshold configurations. In Figure 4 we show the average (over all present UEs) throughput achieved considering the three different threshold levels as well as AT for different offered load values. We can perceive that as the cooperating group shrinks, the performance increases for a specific load. In addition, as the offered load increases, the performance is improved in relation to the others, which is due to the reduction of the exceptional cases. According to the average UE throughput, the AT approach provided a performance in between δ_h and δ_l configurations.

Still from Figure 4, we can perceive that a proper division of UEs among the cooperating and non-cooperating groups can provide gains over the traditional techniques. For the highest threshold value, most of the UEs are selected to perform IA, but in practice they do not benefit from the interference mitigation. On the other hand, when the right UEs are chosen to mitigate interference (smaller threshold values), the proposed scheme performs around 30% better than

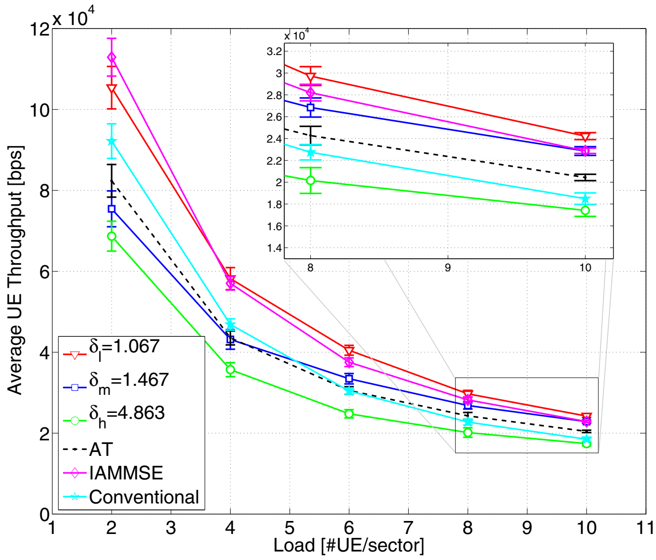

Fig. 4. Comparison of system average throughput over all UEs for the different threshold configurations.

the conventional transmissions, considering δ_l and simulations with 10 UEs per sector. The AT approach has the benefit of automating the process and avoiding empirical threshold selection. Nevertheless, its performance in terms of average UE throughput is still below the one achieved with the best fixed threshold and only slightly better than the traditional techniques for higher loads. Since the considered theoretical capacity expression does not take into account the MCSs, it is not the most suitable metric for a systemic scenario. Therefore, if we rely on the achievable throughput of each UE and consider the values of Geometry and CoMP geometry, this should lead to a better division of the UEs within the right groups and consequently to a performance comparable to that of the best fixed threshold.

IV. Conclusions

This paper has dealt with issues such as the coexistence of Interference Alignment (IA) with resource management, and the potential interference and diversity brought by the multitude of users. By assuming that not all User Equipments (UEs) will benefit from cooperation in a meaningful way, we devised a scheme that identifies those UEs expected to benefit the most; then, both cooperating and non-cooperating transmissions take place within a same CoMP-cell. The proposed method for grouping the users has the advantage of being based on a simple decision metric, CoMP gain, which avoids having to calculate precoders for all different possible combinations.

The transmission strategy consists in classifying the UEs in this manner and, afterwards, establishing cooperating and non-cooperating transmissions alternated in time. In addition, we described the automation of the process of fractioning the amount of TTIs per type of transmission and of classifying to which group each UE should belong. The automatic TTI reservation showed itself as a simple and effective solution, since it dynamically fractions the time resources based on the actual group sizes.

An Adaptive per-UE Threshold (AT) approach has also been proposed, which allows us to avoid having to determine whether a given CoMP-gain threshold will be considered low or high for a given scenario, eliminating an empirical decision. For all conducted tests, AT provided good low and high percentiles, and reasonable medians, in terms of the total CoMP cell instant throughput. In addition, its performance can be further improved by resorting on throughput calculations instead of relying on the capacity metric.

Overall, combining the automatic TTI reservation with the AT approach makes the CoMP-gain-aware transmission strategy simpler to be put in practice, since no empiricism is required. Even though the throughput performance it provides is not the best in terms of mean or median, it achieves reasonable throughput values when considering the extreme percentiles.

Acknowledgement

This work was supported by the Innovation Center, Ericsson Telecomunicações S.A., Brazil, under EDB/UFC.35 and EDB/UFC.42 Technical Cooperation Contracts.

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