MUCICA: A Novel Interference Mitigation Concept for HetNets - Application to the LTE Downlink

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***Abstract*—In a spectrum-sharing heterogeneous network (HetNet), low-power cells such as femtocells are deployed jointly with macrocells, thereby generating interference. To tackle this critical issue in HetNets, we advocate a new interference mitigation concept that combines uncoordinated use of both interference cancellation and interference avoidance at the receiver and transmitter sides, respectively, to benefit from their relative advantages of higher throughput and lower cost, respectively. The resulting new strategy, MUCICA for Mitigation through Uncoordinated Co-channel Interference Cancellation and Avoidance, aims at enhancing the overall system capacity with least increase in computational cost and/or coordination overhead. As one concrete materialization of the new MUCICA concept, we propose on one hand a new downlink interference cancellation (DL-IC) strategy for spectrum-sharing LTE (Long Term Evolution) HetNet that reduces the interference impact on users by optimizing their received signal to interference plus noise ratio (SINR). On the other hand, we propose a dynamic interference avoidance strategy with macrocells' reduced power subframes referred to as dynamic low-power almost blank subframes (DLP-ABS) with reduced transmission power at some specific subframes. When implementing either DL-IC or DLP-ABS, system-level simulations do suggest that both global network performance and user experience in terms of total throughput and received SNR or link-level throughput, respectively, are significantly enhanced, indeed. However, much more significant gains both in performance and cost can be achieved under the new MUCICA concept by properly combining both new DL-IC and DLP-ABS interference mitigation strategies. Indeed, the latter do not require any extra coordination overhead in between and instead adopt each a relatively less stringent operation setup whose relaxation becomes possible owing to the simultaneous operation and unsupervised assistance of the other.**

***Index Terms*—LTE, HetNet, Femto, Interference, Mitigation, Avoidance, Cancellation, Uncoordination.**

I. Introduction

HETNETS integrate small-coverage cells to extend the range and improve the spatial frequency reuse and thereby enhance the user experience. In this work, we are interested in femtocells which have recently emerged as a promising approach to enhance wireless systems' capacity and extend the macrocellular range. Femto base stations are low-power base stations owned and installed by the customer indoors where more than 50% of voice calls and more than 70% of data traffic are generated [1].

However, the ad-hoc deployment of femtocells raises new technical challenges and cross-tier interference [2] that is quite different from conventional interference in homogeneous networks. Consequently, the new network's structure modifies the interference profile in a drastic way that hampers some victim users' connectivity. To deal with these challenges, research efforts are being deployed to address this crucial problem and better exploit the potential benefits of HetNets without compromising the network performance. Several research works have considered the issue of downlink interference mitigation in LTE HetNets [3], [4], [5], [6]. These are mainly categorized into interference cancellation (typically at the receiver), interference avoidance (typically at the transmitter), and interference alignment [4], [7] (typically at both transmitter and receiver). In the latter category, interference coordination or avoidance was widely presented as an efficient approach that applies restrictions on power, time and/or frequency resource management in a coordinated way between cells. Several interference coordination techniques for HetNets [1] mainly divide available resources between macrocells and femtocells in the time-frequency grid. Avoidance techniques were widely used to manage interference, among them power control and frequency reuse techniques. Power control algorithms were developed in order to optimize base stations transmission powers in HetNets [8].

Here, we propose MUCICA for Mitigation through Uncoordinated Co-channel Interference Cancellation and Avoidance, a new concept similar to interference alignment in that it also involves interference mitigation at both the transmitter and receiver sides, yet quite different from it by adopting avoidance instead of precoding at the former and low-cost suppression at the latter in an uncoordinated manner, i.e., without requiring as such any additional information exchange in between. As one concrete materialization of the new MUCICA concept on the downlink[1], we develop on one hand a new DL-IC strategy at the receiver side. IC has indeed the advantage of being relatively simple in concept by requiring little if no coordination effort and overhead in that it allows users to transmit simultaneously without the need for any avoidance through scheduling in time and/or frequency, potentially resulting in higher throughput and spectrum efficiency. IC has, however, the only possible drawback of putting some computational burden on the receiver side. Our newly proposed DL-IC strategy differs from previous IC works in that it relies on new utility functions that maximize SINR (signal to Interference plus Noise Ratio) [9], QoS, and throughput while putting a price on IC's intensive computing efforts for their minimization.

On the other hand, we develop at the transmitter side a new interference avoidance technique that periodically updates macrocells' transmission power during some so-called "blank subframes" to mitigate the downlink cross-tier interference. Recently, few works considered data transmission with reduced macrocell's power, referred to as "almost blank subframes" (ABS) which makes it an interesting field to investigate. Here, we propose a new dynamic low-power ABS (DLP-ABS) where the macrocell's power is no longer nulled but reduced by an amount determined by the channel state and the received interference [23]. Unlike conventional ABS which transmits only reference signals, the newly proposed DLP-ABS allows data transmission at lower power. Macrocell's power is indeed, dynamically updated during special subframes considering power ranges that translate the channel quality experienced by users during previous subframes.

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[1] Please note that MUCICA applies on the uplink as well.

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When implementing either DL-IC or DLP-ABS, system-level simulations do suggest that both global network performance and user experience in terms of total throughput and received SNR or link-level throughput, respectively, are significantly enhanced, indeed. However, much more significant gains both in throughput performance and complexity/overhead cost can be achieved with the new MUCICA concept by properly combining both new interference mitigation strategies. Indeed, the latter do not require any extra coordination overhead in between, in contrast to IA, and instead adopt each a relatively less stringent operation setup whose relaxation becomes possible owing to the simultaneous operation and unsupervised assistance of the other.

The rest of the paper is organized as follows: we discuss in the next section our system model. In section III, we present the newly proposed spectrum sharing DL-IC and DLP-ABS techniques. In section IV, we confirm by simulations the significant gains achieved in terms of total throughput.

II. System model

We consider a spectrum-sharing two-tier LTE HetNet comprising a number of outdoor macrocells, each having a fixed number of indoor femtocells deployed within its coverage area. The latter are said to be attached to their cell's parent macrocell. We suppose also that each user u from the set of users, denoted by $\mathcal{L}$, is attached to a femtocell or a macrocell based on the best received signal strength. The received DL signal of this user is severely affected by high interference received from the set of neighboring cells, consisting of both macrocells and femtocells, denoted by J_u. In fact, each user $u \in \mathcal{L}$ computes its received SINR for any given resource block (RB) numbered r, at each transmission time interval (TTI), using the following expression:

$$\gamma_{u,r} = \frac{L_{M,u,i(u),r} \times L_{S,u,i(u),r} \times P_{i(u),r,tx}}{\sum_{j \in J_u} L_{M,u,j,r} \times L_{S,u,j,r} \times P_{j,r,tx} + \sigma_{u,r}}, \quad (1)$$

where $L_{M,u,i(u),r}$ and $L_{M,u,j,r}(j \in J_u)$ model both the propagation pathloss due to the distance and the antenna gain between the user u and its serving cell $i(u)$ and interfering cell $j \in J_u$, respectively; $L_{S,u,i(u),r}$ and $L_{S,u,j,r}$ model the shadow fading caused by obstacles in the propagation path between the user u and its serving cell $i(u)$ and interfering cell $j \in J_u$, respectively; and $\sigma_{u,r}$ is the power of the additive white Gaussian noise received by user u. Finally, $P_{i(u),r,tx}$ is the transmitted power from the serving cell, $i(u)$, of user u and $P_{j,r,tx}$ is the transmitted power from the interfering cell $j \in J_u$. For the sake of simplifying notations, we adopt the two following compact expressions:

$$P_{u,i(u),r} = L_{M,u,i(u),r} \times L_{S,u,i(u),r} \times P_{i(u),r,tx}$$

and

$$P_{u,j,r} = L_{M,u,j,r} \times L_{S,u,j,r} \times P_{j,r,tx}$$

where $P_{u,i(u),r}$ and $P_{u,j,r}$ denote the received power from the serving cell $i(u)$ and the neighboring interfering cell $j \in J_u$, respectively. Equation 1 then reduces to:

$$\gamma_{u,r} = \frac{P_{u,i(u),r}}{\sum_{j \in J_u} P_{u,j,r} + \sigma_{u,r}}. \quad (2)$$

III. Interference mitigation techniques

Since femtocells operate in the same licensed spectrum owned by the macrocellular service provider, it is crucial to develop robust interference mitigation techniques to handle the cross-tier interference. These schemes should guarantee the QoS requirements of the existing macro-users and effectively enhance the overall system performance with the newly-deployed femto-users. Both interference avoidance and interference cancellation techniques promise to enhance the overall system capacity. Interference cancellation has been considered as a highly performing technique surpassing interference avoidance techniques at the expense of increased complexity at the receiver side. However, interference avoidance offers relatively lower yet interesting capacity enhancement at relatively lower implementation costs at the transmitter side.

Here, we propose a new combination of both interference mitigation techniques: the first, referred to as DL-IC and recently developed by the authors in [10], [11], is based on cancellation at the receiver (cf. section III-A below). While the second, newly developed here and referred to as DLP-ABS, is based on avoidance, at the transmitter (cf. section III-B). Even though each of these two new solutions offers when implemented alone significant improvements, we advocate here their uncoordinated combination with relatively more relaxed setups under the novel MUCICA concept (cf. section III-C) to achieve much better trade-offs between computational/overhead cost and throughput performance gains, yet without requiring any extra coordination overhead in between, in contrast to IA, while adopting each a relatively less stringent operation setup whose relaxation becomes possible owing to the simultaneous operation and unsupervised assistance of the other (cf. section IV).

A. DL-IC interference cancellation at the receiver

To reduce the interference and enhance the user's received SINR, we consider the spectrum-sharing DL-IC strategy proposed in [10], [11]. The receiver of a given user u should properly cancel the received interfering signals. Consequently, the term $\sum_{j \in J_u} P_{u,j,r}$, which represents the resulting received interfering power, must be minimized. To do so, the received interfering powers are multiplied by cancellation coefficients to obtain the resulting residual interfering power $\sum_{j \in J_u} a_{u,j,r} \times P_{u,j,r}$, where $a_{u,j,r}$ $(j \in J_u)$ are the cancellation coefficients to be determined. Therefore, the resulting SINR after the IC strategy is implemented is expressed as follows:

$$\gamma_{u,r} = \frac{P_{u,i(u),r}}{\sum_{j \in J_u} a_{u,j,r} \times P_{u,j,r} + \sigma_{u,r}}. \quad (3)$$

The spectrum-sharing DL-IC strategy is mainly based on computing the optimal cancellation coefficients in order to optimize the user's received SINR. To achieve this goal, a net utility function $U_{net,u}$ has to be maximized for each user u.

In fact, the utility function maximization allows the user to properly select the received interfering signals to cancel. The used utility function is composed of a utility function U_u that represents the degree of user satisfaction, and a cost function C_u which represents the computational cost incurred. The resulting total utility function $U_{net,u}$ and the cost function is expressed as follows:

$$U_{net,u}(\gamma_u) = U_u(\gamma_u) - C_u(\gamma_u). \quad (4)$$

For each user $u \in \mathcal{L}$, we use the same following cost function:

$$C_u(\gamma_u) = \beta\gamma_u, \quad (5)$$

where β is the pricing parameter.

To obtain the optimal values for the cancellation coefficients $a_{u,j,r}$ $(j \in J_u)$, we must compute the optimal SINR, denoted $\hat{\gamma}_u$, which maximizes the net utility function $U_{net,u}$. More details about the proposed utility functions, their expressions, and implementation can be found in [10] and the references therein. To further reduce the computational cost of DL-IC, we define a lower bound, denoted as

A_l, that reflects the cancellation precision, and a number of cancellation constraints N_c, that restricts the number of signals to cancel to those requiring the N_c smallest cancellation coefficients. In fact, imperfections due to channel estimation and signals' reconstruction make it impossible to perform a perfect cancellation of the interfering signals at the requested cancellation ratio or coefficient $a_{u,j,r}$. Therefore, A_l represents the minimum suppression ratio achievable due to IC implementation imperfections or the minimum value that a cancellation coefficient can take [i.e., $a_{u,j,r} = \max_{i \in J_u}(A_l, a_{u,i,r})$]. Results in [10], [11] suggest that $A_l = 10^{-2}$ achieves a good tradeoff between complexity and performance enhancement.

B. DLP-ABS at the transmitter

In HetNets, interference avoidance techniques promise to prevent interference and avoid SINRs degradation. Interference avoidance techniques are interesting since they are implemented at the base station and, hence, do not involve directly the user equipment in the resource management. In this work, we consider a time-domain resource management scheme to reduce the interference based on muting the macrocells' effective transmission during a certain time. This technique has been specified by the 3GPP/LTE organization and referred as almost blank subframe (ABS) since Release 10 [12].

In conventional time domain muting solutions, the base station does not transmit any signal during the muted subframe; which means that the base station's power is nulled. In this case, the scheme is called zero-power ABS. In Release 11, enhanced Inter-Cell Interference Coordination (eICIC) techniques were addressed [13] with reduced power base station transmission or low-power ABS [14] where only reference signals are transmitted. Being a newly addressed topic, ABS is still under investigation [12], [15], [16], [17].

In this work, we consider a new DLP-ABS scheme applied to a HetNet with macrocells and femtocells. We consider to reduce the macrocell's data transmission power since the latter can exploit the X2 interface and so our new proposed strategy is named macrocell's DLP-ABS. We do so also because the femtocell power is already too low compared to the macrocell. Hence, its effect is less sensitive compared to the interference received from macro aggressors.

In our scheme, we consider a macro-femto cellular network where the femto-users are scheduled all the running time with the same maximum permitted femtocell's power. The macro-users are scheduled with full maximum allowed macro power only in the permitted subframes called non ABS subframes.

We define the ABS subframes with a muting period M_G and a muting ratio M_f [18]. By muting period, we refer to each M_G subframes portion over the total number of subframes where we consider DLP-ABS. The subframes with DLP-ABS are the first $M_G \times M_f$ of each portion of M_G subframes. Fig. 1 illustrates the DLP-ABS scheme. During DLP-ABS subframes, the macro base station transmits with a reduced power dynamically adjusted to the channel status observed in the previous subframes and the experienced interference. To adjust macrocell's transmit power, we upgrade the power control conventional expression described in LTE [19] using dynamic variables translating the channel status through power ranges depending on channel quality indicators (CQIs).

At the end of each subframe, the user sends a feedback informing the base station of its current CQIs (Channel Quality Indicators) which indicate the modulation and the coding schemes (MCSs) that were used in the last TTI (Transmit Time Interval) at every RB. These MCSs translate the channel state seen by each user. Then, the base station gathers the CQIs fed from all its attached users and gets the maximum CQI, CQI_{max}, and the minimum CQI, CQI_{min}, over all attached users and all RBs. Having these two values, the base station is able to adjust its power according to the channel state and the interference and so the reduced power does not affect the QoS at macrocells. When the macrocell experiences a high interference level and the UE reports a high MCS, its power should not be reduced too much. When it experiences low interference and the UE reports low MCS, the power can be reduced considerably [20]. For each CQI range, we associate a power range value for power reduction denoted as P_{range} as shown in Table I.

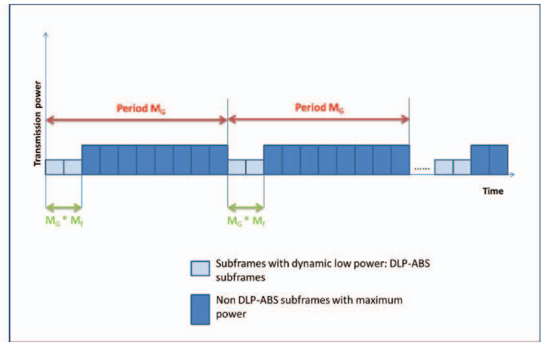

Fig. 1. DLP-ABS subframes period defined in LTE [19] using dynamic variables translating the channel status through power ranges depending on channel quality indicators (CQIs).

TABLE I
SUMMARY OF DLP-ABS STRATEGY.

• P_{range} = {P1, P2, P3}
{IF} cqi $\in \{1, 2, \ldots, 6\}$
• CQI_{range}(cqi) $= 1$, relative to QPSK modulation
• $P_{range}(1) = P1$
{ELSE-IF} cqi $\in \{7, 8, 9\}$
• CQI_{range}(cqi) $= 2$, relative to 16-QAM modulation
• $P_{range}(2) = P2$
{ELSE-IF} cqi $\in \{10, 11, \ldots, 15\}$
• CQI_{range}(cqi) $= 3$, relative to 64-QAM modulation
• $P_{range}(3) = P3$
{END}

At DLP-ABS subframes, the macrocell's power, in each sector s, is dynamically updated as follows:

$$eNB_{pw}(s)[dBm] = \min(eNB_{pw}^{tx}, \max(P_{min}, min(P_0 + P_{pld}, P_{max})) - P_{range}(CQI_{range}^{min}(s)), \quad (6)$$

where $eNB_{pw}(s)$ refers to the newly computed linear power for sector s for the eNodeB, and P_{max}, P_{min}, P_0 (the received interference), and P_{pld} (the pathloss degradation between the eNodeB and attached user) are defined as:

$$P_{max} = 10 \times log10(eNB_{pw}^{tx}) + P_{range}(CQI_{range}^{max}(s)),$$

$$P_{min} = 10 \times log10(eNB_{pw}^{tx}) - P_{range}(CQI_{range}^{min}(s)),$$

$$P_0 = 10 \times log10(eNB(s)_{int}) + P_{range}(CQI_{range}^{max}(s)),$$

$$P_{pld} = 10 \times log10(eNB(s)_{mpd}), \quad (7)$$

where eNB_{pw}^{tx} is the maximum power allowed for the macro base station, $eNB(s)_{int}$ is the received interference of users attached to sector s of the macro eNB and $eNB(s)_{mpd}$ stands for the macroscopic pathloss degradation, and

$$CQI_{range}^{min}(s) = CQI_{range}(CQI_{min}),$$
$$CQI_{range}^{max}(s) = CQI_{range}(CQI_{max}).$$

This expression reduces the eNodeB's transmission power during the DLP-ABS subframes instead of nulling it. Actually, we compensate the loss due to the received interference minus the allowed power reduction relative to the most sensitive MCS case.

C. MUCICA at both the receiver and the transmitter

Both interference avoidance and interference cancellation techniques promise to enhance the overall system capacity. On one hand, interference cancellation has been considered in many works as a highly performing technique surpassing interference avoidance at the cost of high complexity at the receiver side. On the other hand, interference avoidance is interesting in terms of DL capacity enhancement due to its low complexity of implementation at the transmitter side.

Here, we propose an uncoordinated combination of both DL-IC and DLP-ABS strategies detailed previously. Considering the robustness of DL-IC and the high throughput gains it achieves, we intend through this combination to keep the same performance or even to surpass it at lower complexity. Indeed, the performance of DL-IC [10], [11] is proportional to the number of signals to cancel, N_c, referred to as the number of constraints. Hence, high performance achievement is too costly and implies high computational burden at the receiver side. When combining the proposed interference cancellation and avoidance techniques, we alleviate the computational charge at the receiver side by reducing the number of constraints N_c. Thus, the resulting loss in performance is compensated by interference avoidance at the transmitter side without the very demanding requirement of any additional information exchange with the receiver, in blunt contrast to interference alignment approaches. Consequently, the transmitter and the receiver orchestrate interference mitigation almost independently at both sides of the transmission link as described in TableII. On one side, during the DLP-ABS subframes, the transmitter adjusts dynamically its power with respect to the channel status observed in the previous subframes and the experienced interference. On the other side, the receiver cancels the interfering signals with DL-IC.

TABLE II
SUMMARY OF MUCICA IMPLEMENTED WITH THE DL-IC AND DLP-ABS STRATEGIES.

{**IF**} TTI=0
- BS sets transmit power to maximum value eNB_{pw}^{tx}
- UE performs DL-IC and sends feedback(TTI=0)

{**ELSE**}
- {**IF**} subframe is not DLP-ABS
  - BS sets transmit power to maximum value eNB_{pw}^{tx}
  - UE performs DL-IC and sends feedback(TTI)
- {**ELSE**}
  - BS sets transmit power $eNB_{pw}(s)$ as calculated in (6)
  - UE performs DL-IC and sends feedback(TTI)
- {**END**}

{**END**}

TABLE III
SIMULATION PARAMETERS.

Parameters	Macrocell	Femtocell
Cell layout	hexagonal grid of seven cells with three sectors each	circular cell with one sector
Initial UEs number	25 macro or femto UEs in total per macrocell	1 femto UE per femtocell (minimum)
Scheduler	Proportional fair	
Downlink TX scheme	2x2 OLSM MIMO	
Simulation time	$100TTIs * 80$ iterations	
DL-IC [10], [11] and DL-PC [21] parameters	$\alpha_m = 4.5\beta_m$, $\beta_m = 10^{-3}$; $A_l = 10^{-2}$	$\beta_f = 10^4$
DLP-ABS parameters	$[P1\ P2\ P3] = [6\ 3\ 0]\ (dB)$ $M_G = 10$ subframes $M_f = 20\%$	

IV. EVALUATION OF THE PROPOSED INTERFERENCE MITIGATION STRATEGIES

A. Simulation setup

To evaluate the performance of our proposed interference mitigation strategy, combined DL-IC and DLP-ABS, we resorted to an LTE network system-level simulator that generates a region of interest (ROI) composed of 7 hexagonal macrocells that follow an urban macrocellular environment model [22]. Depending on the simulation scenario, it randomly populates this ROI by femtocell sites up to a requested average number of femtocells per macrocell that follow an indoor hotspot channel model [22]. A total of 25 UEs are randomly deployed, uniformly, inside each macrocell in such a way that at least one UE is initially attached to a femtocell (i.e., we hence make sure that we account for genuinely active femtocells only). However, during simulations, each UE can request handover, if necessary, to the cell offering best coverage. The simulation parameters are summarized in Table III and table in [23].

B. Simulation results and analysis

In this section, we proceed to system-level simulations by evaluating each interference mitigation strategy (DL-IC and DLP-ABS) apart to isolate its strengths and weaknesses. We then assess the advantages of their combination in terms of performance enhancement and complexity reduction. The first evaluation parameter, the total throughput, is the sum of link-level throughputs over all users. The second evaluation parameter, the complexity, is expressed as a function of the number of constraints.

1) DL-IC evaluation: In [10], [11], we studied our DL-IC strategy and we evaluated its performance. We showed that DL-IC depends on several tuning parameters, assessed the impact of the latter on performance, and optimized their values to maximize throughput. For more details, we refer the readers to [10], [11]. Simulations showed that DL-IC enhances considerably the system performance compared to a homogeneous network and a HetNet without DL-IC.

To confirm the robustness of the DL-IC strategy, after it has been optimized both in throughput performance and implementation cost against a basic HetNet setting without IC, we considered benchmark techniques for performance comparisons, namely the dynamic DL power control (DL-PC) algorithm for LTE HetNet proposed in [19], and the conventional FFR discussed in [2] without power control on femtocell sub-bands. Then, we proposed as a third benchmark, an adaptive subband allocation (ASA) scheme where macrocells use the entire spectrum and femtocells exploit only a fraction of all resources.

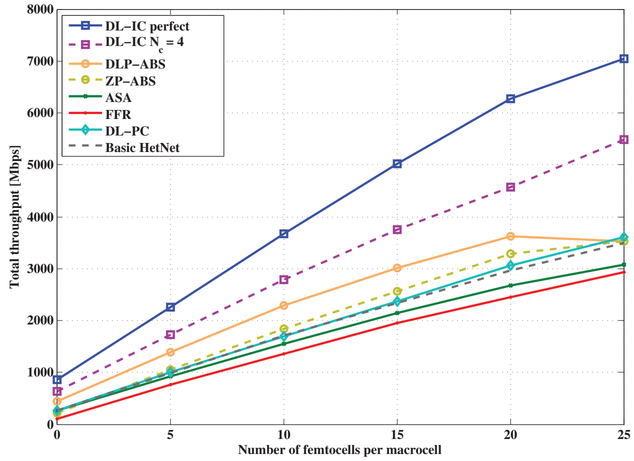

Fig. 2. Total network throughputs of our proposed interference mitigation techniques and benchmark techniques versus the number of femtocells per macrocell.

ASA was described in [11] and results were presented in [10], [11]. In Fig. 2, we plot the total network throughput achieved by our DL-IC strategy (with different setups) and by DL-PC, FFR and ASA. Taking basic HetNet as a reference against which throughput performance is gauged [23], we observe that DL-PC offers only a modest throughput gain of about 2% per additional femocell site, FFR suffers from severe throughput losses (due to its rigid frequency partitioning), while ASA offers only a modest throughput gain. In contrast, the optimized DL-IC in terms of performance vs. complexity tradeoff offers much more significant gains, about the same, and sitting only almost halfway from the potential maximum gains achievable with perfect IC implementation.

2) DLP-ABS evaluation: In the following, we evaluate the performance of our DLP-ABS strategy alone. DLP-ABS permits to reduce the received interference seen by both macro and femto-users which leads to total system capacity enhancement. We compare DLP-ABS to the previously described benchmark strategies and the conventional zero-power ABS (ZP-ABS). With ZP-ABS, the macrocell does not transmit during the muted subframe [14]. We show in Fig. 2 that our proposed DLP-ABS resource management strategy performs better[2] than all considered benchmark schemes. This makes DLP-ABS a promising technique, mainly because it does not overload the system with extra feedback exchange on the top of being a transmitter-based process that reliefs the receiver's computational burden and battery consumption.

3) MUCICA evaluation: As showed in the previous section, LP-ABS is a promising technique to enhance the systems performance with low complexity. Here, we evaluate the performance of MUCICA that combines both DLP-ABS and DL-IC in an uncoordinated manner, to take advantage of their respective strengths while avoiding their weaknesses, thereby resulting into lot better total network throughput performance vs. complexity trade-offs.
First, we evaluate the performance of both DL-IC and DLP-ABS strategies versus the number of constraints N_c for different numbers of femtocells. We notice from Fig. 3 that DLP-ABS outperforms DL-IC for $N_c = 1$ and equates it in throughput starting right away with N_c as small as 2 for either 5 or 10 femtocells per macrocell and 1 for higher femtocell densities, and surpass it for larger values of N_c. This behavior supports unambiguously our idea of combining DLP-ABS and DL-IC to reduce the number of cancellation constraints and, hence, the overall complexity. Indeed, the capacity loss resulting from reducing the number of constraints of DL-IC can be compensated and even surpassed by its combination in and uncoordinated manner with DLP-ABS for interference avoidance at the transmitter. It is precisely the main idea behind the new MUCICA concept we advocate in this work as an interference mitigation alternative with much more attractive trade-offs in terms of performance gains vs. complexity costs.

[2]In the case of 25 genuinely-active femtocells per macrocell, there are no more UEs served by the macrocell to be managed by DLP-ABS or ZP-ABS. Hence, the latter reduce to the basic HetNet benchmark.

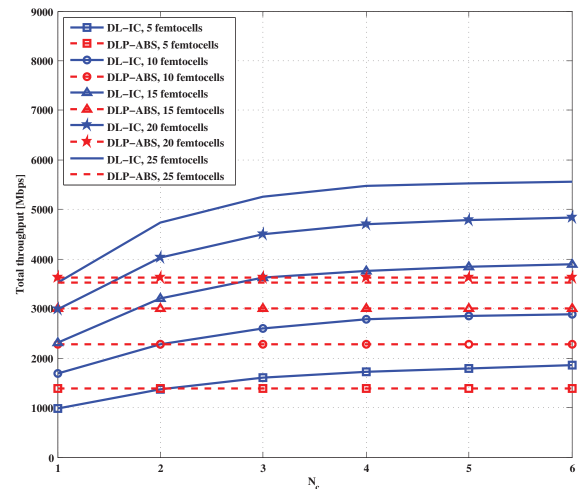

Fig. 3. Total network throughput of DLP-ABS performance and DL-IC versus the number of constraints N_c.

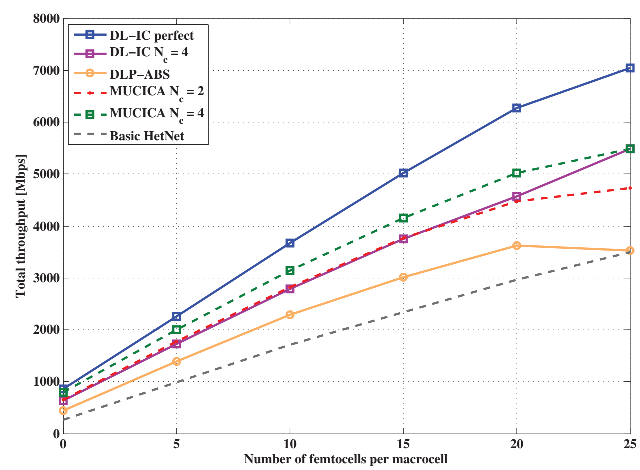

Fig. 4. Total network throughput performance of MUCICA compared to DL-IC and DLP-ABS versus the number of femtocells per macrocell.

We first compare in Fig 4 the performance of MUCICA compared to basic HetNet, DL-IC and DLP-ABS versus the number of femtocells per macrocell. We notice that MUCICA with $N_c = 2$ matches in throughput performance DL-IC with $N_c = 4$ for 5, 10 and 15 femtocells per macrocell. However, MUCICA outperforms DL-IC with $N_c = 4$.

TABLE IV
THROUGHPUT GAIN VS. COMPLEXITY GAIN TRADE-OFFS ACHIEVED BY MUCICA AGAINST DL-IC FOR DIFFERENT NUMBERS OF FEMTOCELLS PER MACROCELL.

	DL-IC		MUCICA		Throughput gain	Complexity gain		
	N_c	$\mathcal{T}$ [Mbps]	N_c	$\mathcal{T}$ [Mbps]		$O(N_c)$	$O({N_c}^2)$	$O({N_c}^3)$
5 femtocells	6	1861	3	1926	3.49 %	50.00 %	75.00 %	87.50 %
			2	1781	-4.29 %	66.66 %	88.88 %	96.29 %
	5	1798	3	1926	7.12 %	40.00 %	64.00 %	78.40 %
			2	1781	-0.94 %	60.00 %	84.00 %	93.60 %
10 femtocells	6	2881	3	3027	5.06 %	50.00 %	75.00 %	87.50 %
			2	2813	-2.36 %	66.66 %	88.88 %	96.29 %
	5	2845	3	3027	6.39 %	40.00 %	64.00 %	78.40 %
			2	2813	-1.12 %	60.00 %	84.00 %	93.60 %
20 femtocells	6	4828	4	5025	4.08 %	33.33 %	55.55 %	70.37 %
			3	4827	-0.02 %	50.00 %	75.00 %	87.50 % %
	5	4792	3	4827	0.73 %	40.00 %	64.00 %	78.40 %
			2	4476	-6.59 %	60.00 %	84.00 %	93.60 %

In Fig. 5, we compare the throughput performance of both MUCICA and DL-IC versus the number of constraints N_c for different femtocell densities. As expected, for any given values of N_c and femtocell density, MUCICA always outperforms DL-IC. The throughput gain decreases, however, with the either values of N_c or femtocell density increasing. This is, however, hardly surprising. On one hand, indeed, as the number of constraints N_c increases, IC becomes more efficient thereby leaving little room for interference avoidance - through DLP-ABS - to contribute to the aggregate gain in any noticeable way. On the other hand, as expected, since the number of femtocells per macrocell increases, much more users are offloaded from macrocells to femtocells thereby further reducing the impact of interference avoidance - through DLP-ABS - over an increasingly shrinking set of macrocell UEs. In Tab. IV, we compare the performance vs. complexity trade-offs achieved by both MUCICA and DL-IC for different femtocell density values. The complexity gain is obtained, for a given complexity order $O({N_c}^k)$, as $1-(\frac{N_c(MUCICA)}{N_c(DL-IC)})^k$, where $N_c(MUCICA)$ and $N_c(DL-IC)$ are the numbers of constraints required by MUCICA and DL-IC, respectively, to achieve about the same throughput. It is here that we illustrate unambiguously and unequivocally the clear-cut benefits of the novel interference mitigation concept, MUCICA, both in performance and complexity.

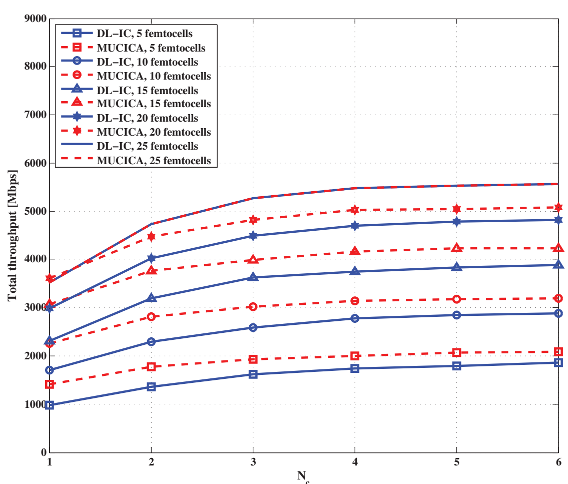

Fig. 5. Total network throughput of MUCICA and DL-IC versus the number of constraints N_c.

We have already reported in Fig. 3 that DLP-ABS does not require more than one or two constraints to match DL-IC in performance and that it surpasses the latter with larger values of N_c. Here, MUCICA is in turn able to perform nearly as well as DL-PC with large values of N_c (i.e., 5 or 6) by exploiting only half those numbers of constraints, thereby enabling significant complexity gains ranging from over 30 to 90 % depending on whether the complexity order in N_c is linear, square, or cubic, while still largely outperforming DLP-ABS. With half the number of constraints, MUCICA achieves about the same performance as DL-IC (at low values of N_c) or better (at higher values of N_c).

V. CONCLUSION

In this paper, we proposed MUCICA, a new concept that combines both interference cancellation and interference avoidance in an uncoordinated manner: the first is as highly robust as intricate while the second is relatively less efficient but simpler. When combined together, their strengths nicely compensate for their weaknesses resulting thereby in a novel best-of-the-two-worlds interference mitigation technique. Simulation results suggest that the novel MUCICA concept, implemented here with the new DLP-ABS and DL-IC strategies, can reduce the number of cancellation constraints and as such the complexity while still achieving better throughput. Gains are particularly very high at relatively lower cancellation constraints and femtocells density and still significant at a higher femtocells density.

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