Combined Interference Cancellation and Avoidance Over the Downlink of Spectrum-Sharing LTE HetNet

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***Abstract*—In a spectrum-sharing heterogeneous network (HetNet), low-power small cells such as femtocells are deployed jointly with macrocells. This new cell layer generates interference that degrades network performance. To mitigate this critical issue in HetNets, we combine both interference cancellation and interference avoidance to benefit from their respective advantages on the downlink of LTE (Long Term Evolution). On one hand, a new downlink interference cancellation (DL-IC) strategy reduces the interference impact on users by optimizing their received signal to interference plus noise ratio (SINR). On the other hand, a new low-power almost-blank subframes (LP-ABS) policy minimizes the effect of downlink interference on femtocells and neighboring macrocells by reducing the transmit power of macrocells during special subframes. When implementing DL-IC and LP-ABS separately, 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 complexity can be achieved by combining newly proposed DL-IC and LP-ABS interference mitigation strategies.**

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

I. Introduction

HetNet integrates small coverage cells such as femtocells, picocells, or microcells and small nodes such as relay nodes, in conjunction with the existing macrocells. These small nodes are supposed to extend the range and improve the spatial frequency reuse to deliver a better user experience. In our case, we are interested in femtocells which have recently emerged as a promising approach to enhance wireless systems' capacity and to extend the macrocellular range. Femto base stations are low-power base stations owned and installed by the customer inside buildings such as homes, enterprises, shopping malls, metro stations, hospitals, etc [1] where more than 50% of voice calls and more than 70% of data traffic are generated; facts that emphasize their advantage of promoting indoors communications.

However, the ad-hoc femtocells' deployment raises new technical challenges and cross-tier interference related problems that result into unprecedented interference scenarios. Consequently, the new network's structure modifies the interference profile in drastic way that hampers some victim users' connectivity.

Downlink interference mitigation in LTE HetNets are mainly categorized into interference cancellation (typically at the receiver), interference avoidance (typically at the transmitter), and interference alignment. 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 [2] 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 [4]. Conventional fractional frequency reuse (FFR) divides the available spectrum into several subbands and assigns them to the cells in such a way that interference is reduced. The adaptive FFR was adopted in several works [3] by updating subband allocation in a dynamic way properly adjusted to the interference levels so as to achieve even higher SINRs while allowing much better spectrum usage.

Interference alignment (IA) was recently proposed as a cooperative transmission technique [5] that implements precoding matrices at all transmitters to align the interference and confine it in the smallest subspace possible at the receiver side to give the desired signal more degrees of freedom. IA is a powerful technique that was widely studied for homogeneous networks (e.g., [6]). Later, some works focused on IA for HetNets (e.g., [7]). However, IA needs cooperation between the transmitter and the receiver to suppress interference that entails a huge computational cost to find the IA solution over each subcarrier making it unpractical for dense systems with many transmitter/receiver pairs. In [5], for instance, IA was studied only at the link level and only for a simple scenario of a small number of users.

Here, we consider an approach similar to IA in that it also involves interference mitigation at both the transmitter and receiver sides, yet by adopting avoidance instead of precoding at the former and low-cost suppression at the latter without any costly information exchange required in between. At the receiver side, we develop a new strategy for spectrum-sharing downlink interference cancellation (DL-IC). IC has indeed the advantage of being relatively simple in concept by requiring little coordination effort and overhead and by allowing users to transmit simultaneously without the need for any avoidance by 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 proposed DL-IC strategy differs from previous IC works in that it relies on new utility functions that maximize SINR, QoS and throughput while putting a price on IC's intensive computing efforts for their minimization.

At the transmitter side, we develop a new interference avoidance technique based on the so-called "blank subframes" concept which periodically mutes the macrocells' transmissions during some subframes' duration. In this concept, macrocells are deprived from transmitting data during a number of subframes. Recently, few works considered data transmission with reduced macrocell's power, referred to as "almost blank subframes" (ABS). Here, we propose a new dynamic low-power ABS (LP-ABS) where the macrocell power is no longer muted but reduced to properly adjusted levels that depend on the channel state and, hence, the received interference.

When implementing DL-IC and LP-ABS separately, 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 complexity can be achieved by combining the newly proposed LD-IC and LP-ABS interference mitigation strategies.

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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 femtocell'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 in many works as a highly performing technique surpassing interference avoidance techniques at the expense of increased complexity at the receiver side. Interference avoidance offers relatively lower yet interesting capacity enhancement at relatively lower implementation costs at the transmitter side, especially on the downlink.

In this work, precisely, we propose a novel joint exploitation of both interference mitigation techniques: The first, recently developed by the authors in [8] and referred to as DL-IC, is based on cancellation at the receiver (cf. section III-A below). While the second, newly developed here and referred to as LP-ABS, is based on avoidance, at the transmitter (cf. section III-B). Even though each solution offers separately significant improvements, we advocate here an ad hoc yet novel combination of both (cf. section III-C) that achieves a much better trade-off between computational costs and performance gains and that outperforms each new technique when implemented separately (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, the interference cancellation technique that we proposed in [8]. 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 the 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.

More details about utility functions expressions and implementation were described in [8] and the references therein.

B. LP-ABS interference avoidance at the transmitter

Interference avoidance techniques are interesting since they are implemented at the base station and hence do not involve directly the user equipment in resource management. In this work, we consider a time-domain resource management technique based on muting the macrocells' effective transmission during a certain time. This technique has been specified by the 3GPP/LTE organization as Almost Blank Subframe (ABS) since Release 10 [13].

In conventional time-domain muting solutions, the base station does not transmit any signal during the muted subframe, meaning that the base station power is nulled. In this case, the scheme is called zero ABS. In Release 11, enhanced Inter-Cell Inerference Coordination (eICIC) techniques were addressed [11] with reduced power at the base station labeled as low-power ABS [12]. Being a newly addressed topic, ABS is still under investigation [13], [14], [15], [16].

In this work, we consider a LP-ABS scheme applied to a HetNet whith macrocells and femtocells. We consider to reduce the macrocell's power since the latter can exploit the X2 interface. We do so also because the femtocell power is already too low compared to the macrocell's. Hence, its effect is less significant than 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. By muting period, we refer to each M_G subrames portion over the total number of subframes where we consider LP-ABS. The subframes with LP-ABS are the first $M_G \times M_f$ of each portion of M_G subframes. Fig. 1 illustrates the LP-ABS scheme.

During the LP-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. At the end of each subframe, the user sends feedback information to the base station about its current CQIs (Channel Quality Indicators) which indicate the modulation and the coding schemes (MCSs) 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 in such a way that 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. And when it experiences low interference and the UE reports low MCS, the power should be reduced considerably [19]. For each CQI range, we associate a power range value for the power reduction denoted as P_{range}. We summarize the CQI to P_{range} translation in Table I.

TABLE I
SUMMARY OF LP-ABS STRATEGY.

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

At ABS subframes, the macro base station power, at each sector s, is dynamically updated as follows:

$$eNB_{pw}(s)[dBm] = - P_{range}(CQI^{min}_{range}(s)) + max(P_{min}, min(P_0 + P_{offset}, P_{max})) \quad (4)$$

where $eNB_{pw}(s)$ refers to the newly computed linear power for sector s of the eNodeB and

$$CQI^{min}_{range}(s) = CQI_{range}(CQI_{min})$$
$$CQI^{max}_{range}(s) = CQI_{range}(CQI_{max})$$

and P_{max}, P_{min}, P_0 (the received interference), and P_{offset} (the pathloss degradation between the eNodeB and attached users) are defined as:

$$P_{max} = 10 \times log10(eNB^{tx}_{pw}) + P_{range}(CQI^{max}_{range}(s)) \quad (5)$$
$$P_{min} = 10 \times log10(eNB^{tx}_{pw}) - P_{range}(CQI^{min}_{range}(s)) \quad (6)$$
$$P_0 = 10 \times log10(eNB(s)_{interf}) + P_{range}(CQI^{max}_{range}(s)) \quad (7)$$
$$P_{offset} = 10 \times log10(eNB(s)_{pathloss}) \quad (8)$$

where eNB^{tx}_{pw} is the maximum power allowed for the macro base station, $eNB(s)_{interf}$ is the received interference at sector s of the macro eNB and $eNB(s)_{pathloss}$ stands for the macroscopic pathloss degradation.
This expression reduces the eNodeB's transmission power during the 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

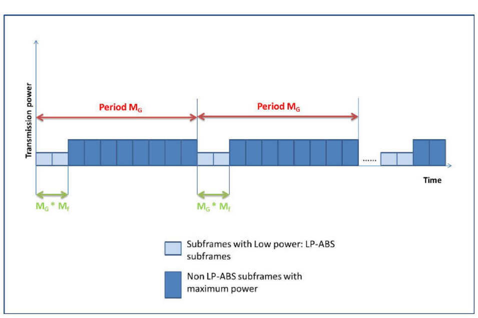

Fig. 1. LP-ABS subframes period and ratio illustration.

C. Combined DL-IC at the receiver and LP-ABS at the transmitter

Here, we propose a combination of both DL-IC and LP-ABS strategies previously detailed. 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.
The performance of DL-IC [8] is proportional to the number of signals to cancel, 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. 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 carry out interference independently as described in Table II. On one side, during the LP-ABS subframes, the transmitter adjusts dynamically its power with regards 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 COMBINED DL-IC/LP-ABS STRATEGY.

if TTI=0
  Transmitter: power = eNB^{tx}_{pw}
  Receiver performs DL-IC and sends feedback(TTI=0)
else
  if subframe is not LP-ABS subframe
    Transmitter: power = eNB^{tx}_{pw}
    Receiver performs DL-IC and sends feedback(TTI)
  else
    Transmitter performs LP-ABS(feedback(TTI-1)), power computed
    as in section III-B
    Receiver performs DL-IC and sends feedback(TTI)
  end
end

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 LP-ABS, we used an LTE network system-level simulator. This simulator generates a region of interest (ROI) composed of 7 hexagonal macrocells. Depending on the simulation scenario, it randomly populates this ROI by femtocell sites up to a requested average number of femtocells per macrocell. The MUEs are randomly deployed inside each macrocell sector. Each FUE is initially attached to a femtocell. However, during the simulation, each UE can request handover, if necessary, to the cell offering best coverage. The simulation parameters are summarized in Table III.

B. Simulation results and analysis

In this section, we evaluate the proposed interference mitigation strategies by simulations. To do so, we proceed by studying each technique apart to isolate their strengths and weaknesses. Then, we assess the advantages of their combination in terms of performance enhancement and complexity reduction.

1) DL-IC evaluation: In [8], 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 detailed results, the readers can refer to [8]. Simulations showed that DL-IC enhances considerably the system performance compared to a

TABLE III
SIMULATION PARAMETERS.

Parameters	**Macrocell**	**Femtocell**
Carrier frequency	2 GHz	
Bandwith	5 MHz (shared)	
N	25 RBs,12 subcarriers per RB	
Cell layout	hexagonal grid of 7 3 sectors' cells	circular cell, 1 sector per cell
Cell size	250 m	20 m
Antenna gain pattern	TS 36.942	Omnidirectionnal
Max antenna gain	15 dBi	0 dBi
Max Tx power	43 dBm	20 dBm
UE receiver noise figure	9 dB	9dB
Thermal noise level	-174 dBm/Hz	-174 dBm/Hz
Pathloss model	Cost 231 urban macro	Indoor Hotspot
Initial UEs number	25 UEs	1 UE
UEs speed	30 Km/h	3 Km/h
Schedular	Proportional Fair	
Simulation time in TTIs	1000	
DL-IC strategy parameters	$\alpha_m = 4.5\beta_m$	$\beta_f = 10^4$ [18]
LP-ABS strategy parameters	$[P1\ P2\ P3] = [6\ 3\ 0](dB)$ $M_G = 10$ subframes $M_f = 2\%$	

homogeneous network and a HetNet without DL-IC.

To confirm the robustness of 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 [17], the conventional FFR without power control on femtocell subbands. 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. ASA was described in [9]. Results of comparisons were presented in [8] and [9].

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, and translate them into throughput gains in Fig. 3. Taking basic HetNet as a reference against which throughput performance is gauged, DL-PC offers only a modest throughput gain of about 2% per additional femocell site against basic HetNet. We observe in Fig. 4 that FFR suffers from throughput losses (due to its rigid frequency partitioning) while ASA offers only a modest throughput gain. In contrast, both proposed DL-IC versions - optimized in terms of performance vs. complexity tradeoff offer much more significant gains, about the same, and sitting only almost halfway from the potential maximum gains achievable with perfect IC implementation.

2) LP-ABS evaluation: In the following, we evaluate the performance of our LP-ABS strategy alone. LP-ABS reduces the interference at both macro and femto users leads to total system capacity enhancement. We compare LP-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 [12]. We show, in Fig. 5, that our proposed resource management strategy gives better results than the benchmark schemes. This makes LP-ABS a promising technique, mainly because it does not overload the system with extra feedback exchange being a transmitter-based process that reliefs the receiver's computational burden and battery consumption.

3) Combined DL-IC/LP-ABS performance evalaution: As showed in the previous section, LP-ABS is a promising technique to enhance the system's performance with low complexity. Here, we evaluate the performance of LP-ABS combined with DL-IC to benefit from their respective strengths.

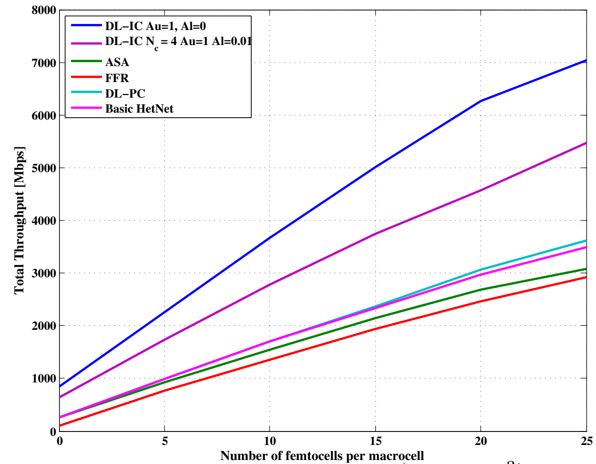

Fig. 2. Total network throughputs ($\beta_m = 10^{-3}$).

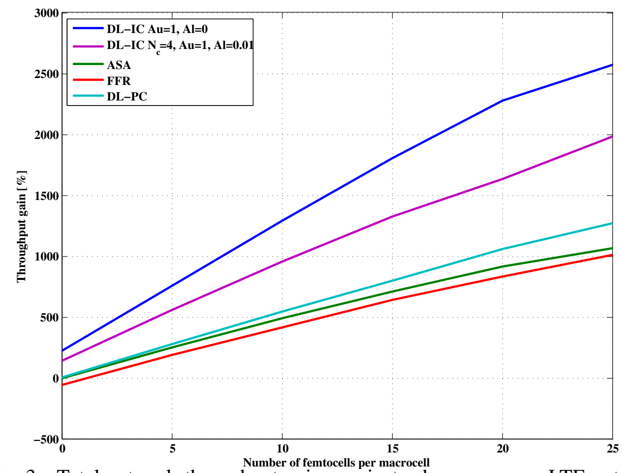

Fig. 3. Total network throughput gains against a homogeneous LTE network ($\beta_m = 10^{-3}$).

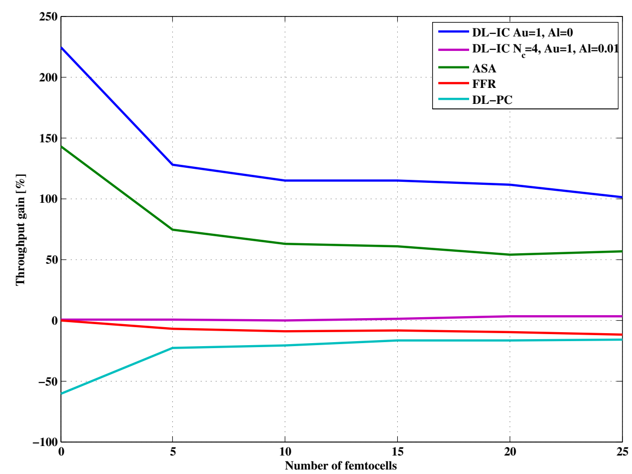

Fig. 4. Network throughput gains against a basic LTE HetNet without IC ($\beta_m = 10^{-3}$).

First, we evaluate the performance of both DL-IC and LP-ABS strategies for different numbers of femtocells. We notice from Fig. 6 that LP-ABS outperforms DL-IC for $N_c = 1$ and equates it for $N_c = 2$ with 5 and 10 femtocells per macrocell. We confirm this observation in Fig. 7 where we present the variation of LP-ABS and DL-IC (for $N_c = 1$, $N_c = 2$ and $N_c = 4$). This behavior supports unambiguously our idea of combining LP-ABS and DL-IC to reduce the number of cancellation constraints. The capacity loss resulting from reducing the number of constraints of DL-IC can be compensated through LP-ABS with interference avoidance at the transmitter.

Then, we study the behavior of LP-ABS when combined with DL-

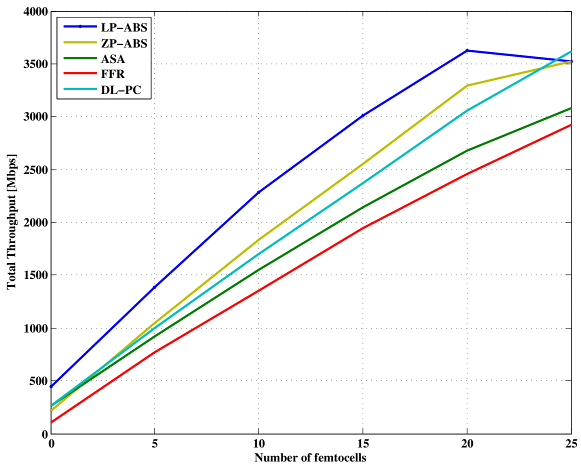

Fig. 5. DL-ABS performance compared to benchmark strategies through total network throughput.

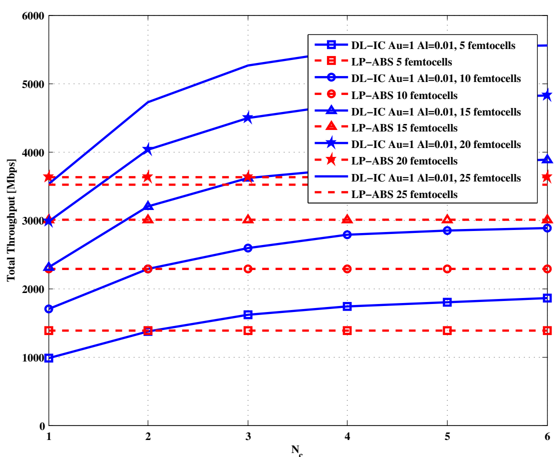

Fig. 6. DL-ABS performance compared to IC versus N_c.

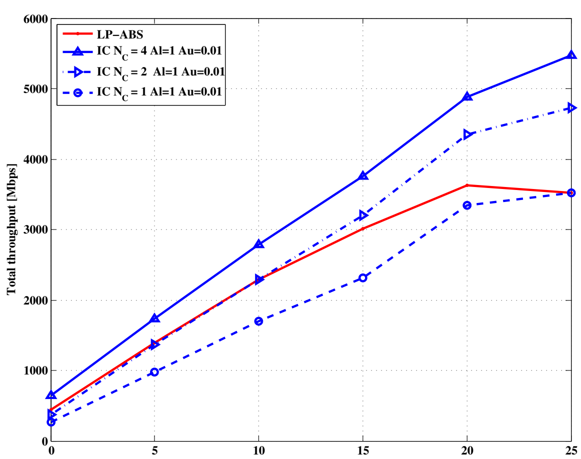

Fig. 7. DL-ABS performance compared to DL-IC versus the number of femtocells.

IC. Results in Fig. 8 suggest that combined LP-ABS/DL-IC strategy gives a capacity enhancement of 42.3% and 12.35% for $N_c = 1$ and $N_c = 6$, respectively, compared to DL-IC alone with 5 femtocells per macrocell. We notice that the gain decreases with N_c increasing due to the significant gains of DL-IC with large cancellation constraints. In fact, DL-IC is able to suppress even more interfering signals with relatively larger constraint numbers. We also notice that the gain decreases when increasing the number of femtocells, as expected, since the number of users attached to the eNodeBs and hence the interference from macrocells, respectively.

At 5 femtocells per macrocell, the combined LP-ABS/DL-IC with

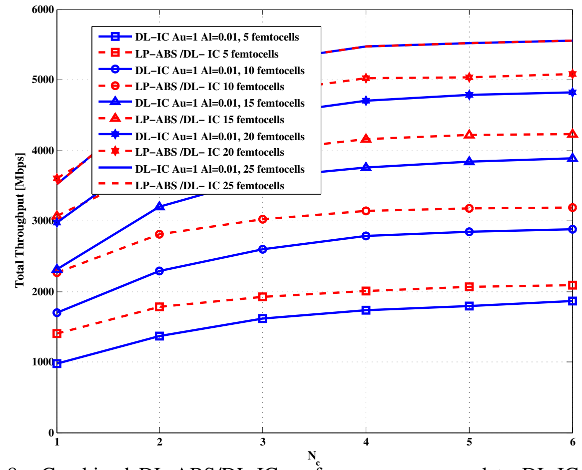

Fig. 8. Combined DL-ABS/DL-IC performance compared to DL-IC versus the number of constraints.

$N_c = 3$ exceeds DL-IC with $N_c \geq 3$. These results suggest that minimizing the number of cancellation constraints leads to lower complexity at the user equipment, yet with better system performance than the one achieved by DL-IC alone. Clearly, our combined DL-ABS/DL-IC strategy gives remarkable throughput gains at relatively lower computational complexity.

V. Conclusion

In this paper, we proposed a new combination of interference cancellation and interference avoidance techniques: 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 our new combined LP-ABS/DL-IC strategy can reduce the number of cancellation constraints, and so the complexity, while still achieving better throughput performance. The gains are significantly important, especially with relatively lower cancellation constraints and lower femtocell's density, and still significant with relatively high numbers of femtocells.

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