Downlink Interference Cancellation Strategy for Shared-Spectrum LTE HetNet

(Invited Paper)

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***Abstract*—In a heterogeneous network (HetNet), femtocells are deployed jointly with macrocells. This new cells' layer added to the network generates interference which would hamper neighboring macro user equipment (MUE) and femto user equipment (FUE) transmissions. In fact, this interference results in degradation of the network performance. In this paper, we propose a downlink interference cancellation (DL-IC) strategy for shared-spectrum LTE (Long Term Evolution) HetNet. This DL-IC strategy aims to reduce the interference impact on users by optimizing their received signal to interference plus noise ratio (SINR) using new utility functions for both FUEs and MUEs. These utility functions allow relaxation of the cancellation ratios in order to reduce implementation complexity while maximizing SINR, QoS and throughput. We support by different system-level simulations that both global network performance and user experience in terms of total throughput and received SNR or link-level throughout, respectively, are significantly enhanced. Throughput gains achievable by the new DL-IC strategy can reach as much as 200% against a homogeneous LTE network without IC along with an extra 48% per additional femtocell base station in a basic shared-spectrum LTE HetNet without IC.**

***Index Terms*—LTE HetNet, Femtocell, Macrocell, DL interference, Cancellation, SINR, Throughput.**

I. Introduction

Mobile communication systems undergo constant growth in terms of number of subscribers. In fact, the ITU organisation confirms that by the end of 2011 the number of mobile services subscribers reached 6 billion around the world, with a penetration factor of 86% [1]. In addition, these users require increasingly better quality of service and a wide coverage characterized by a strong signal, specifically in low coverage areas.

To cope with these challenges, a new concept of Heterogeneous Network (HetNet) was adopted. In HetNet, the network integrates small coverage cells, called femtocells, in conjunction with the existing macrocells. This new cells' layer has been adopted by many wireless communication systems to increase their capacity, to maintain their coverage and to meet the quality of service (QoS) requested by their customers [2]. Among these systems, Long Term Evolution (LTE) developed by 3rd Generation Partnership Project (3GPP) has envisaged femtocells since release 8, with more complete specifications in LTE release 10 (LTE-Advanced) [3]. However, these new cells generate more interference that hampers some victim users' connectivity. Consequently, several research efforts are underway to address this crucial problem and thereby allow full exploitation of the potential benefits of HetNet without hindering the network's performance.

Several research works have tackled the issue of DL interference in LTE HetNet network with different approaches. Interference coordination was widely presented as an efficient approach that applies restrictions on DL time and frequency resources management in a coordinated way between cells. Several interference coordination techniques for HetNet were discussed in [4] and [5]. Likewise, power control algorithms were widely developped in order to optimize base stations' transmission powers in HetNet, for exemple in [6] and [7]. More recently, interference alignment was developed to simplify interference suppression at the UE receivers owing to coordinate between multiple transmittersthat is able to align mutual interference at the receivers. For example, [8] proposed an interference alignment technique that aims to mitigate DL interference in cellular networks. Furthermore, an interference rejection combining (IRC) receiver was proposed to perform spatial suppression of interfering signals in [9]. The latter investigated the performance gain achieved by the IRC receiver combined with an antenna selection technique in a femtocell co-channel interference scenario.

In this paper, we develop a new strategy for shared-spectrum 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. The new DL-IC strategy we propose 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 efforts for their minimization. System-level simulations suggest that the new DL-IC strategy can potentially offer, at low computational cost, as much as 200% against a homogeneous LTE network without IC along with an extra 48% per additional femtocell base station in a basic LTE HetNet without IC.

The rest of the paper is organised as follows: We discuss in the next section our system model. In section III, we develop

Work supported by a Canada Research Chair in Wireless Communications and the Discovery Grants Program of NSERC.

the proposed shared-spectrum DL-IC strategy. In section IV, we confirm by simulations the significant gains achieved in terms of SINR and throughput of both MUEs and FUEs.

II. System model

We consider a shared-spectrum HetNet LTE network composed by two different cell layers: outdoor macrocells and indoor femtocells. We suppose also that each user u from the set of users, denoted by $\mathcal{L}$, is attached to a femtocell or a macrocell. The received DL signal of this user is severely affected by high interference received from the set of neighboring cells, denoted by J_u. In fact, each user $u \in \mathcal{L}$ computes its received SINR in resource block (RB), 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 $\gamma_{u,r}$ is the received SINR, $L_{M,u,i(u),r}$ 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.

For the sake of simplifying notations, we adopt the two following 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. Proposed shared-spectrum DL-IC strategy

In order to reduce interference and enhance the user's received SINR, 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. Analytically, we multiply the received interfering powers 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 cancellation coefficients to be determined. Therefore, the post-IC SINR (i.e., resulting SINR after the IC strategy is implemented) is 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 main purpose of the proposed shared-spectrum DL-IC strategy is to compute the optimal cancellation coefficients that optimize the user's received SINR.

In order to achieve this objective, we define for each user u a net utility function $U_{net,u}$ to be maximized. In fact, utility and cost functions were widely used in power and resources allocation algorithms, in addition to some interference alignment solutions. However, to the best of our knowledge, the utility function concept was not previously exploited in IC for HetNet. Furthermore, the utility function maximization allows the user to properly select the received interfering signals to be cancelled and to enhance its received SINR. Therefore, we use the standard definition of a utility function of network base stations which is composed by a utility function U_u that represents the degree of user satisfaction, and a cost function C_u which represents the cost incurred. The resulting function $U_{net,u}$ is expressed as follows:

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

The cost function is introduced to represent the increasing computational cost incurred by a more accurate cancellation process with reduced implementation errors. Indeed, perfect cancellation [i.e. $a_{u,j,r} = 0$ $(j \in J_u)$] cannot be realized in practice. Even more, very accurate interference cancellation cannot be implemented without requesting a heavy computational burden. 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 be determined.

In order to determine 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 $U_{net,u}$. Therefore, we use the expression of the cost function in eq. (5) and take the derivative of eq. (4) with respect to the variable γ_u as follows:

$$U_u^{'}(\hat{\gamma}_u) - \beta = 0 \Longleftrightarrow \hat{\gamma}_u = U_u^{'-1}(\beta) \,. \quad (6)$$

Consequently, from eqs. (3) and (6), the cancellation coefficients $a_{u,j,r}(j \in J_u)$ can be expressed as follows:

$$a_{u,j,r} = \frac{1}{\jmath_u P_{u,j,r}} \left[\frac{P_{u,i(u),r}}{U_u^{'-1}(\beta)} - \sigma_{u,r} \right] \quad (7)$$

where $\jmath_u$ is the cardinality of the set of interfering cells [$\jmath_u = Card(J_u)$].

In the following, we define the utility functions of both the MUE and the FUE.

A. MUE utility function and IC coefficient

For each MUE $u \in \mathcal{L}_m$, we define its utility function so as to reflect its degree of satisfaction in terms of QoS as follows [10]:

$$U_{m,u}(\gamma_u) = \frac{1}{1 + \exp(-\alpha_m \gamma_u)} \quad (8)$$

where $\mathcal{L}_m$ denotes the set of MUEs and α_m is a parameter that controls the steepness of the utility function. It is observed that a higher SINR $\hat{\gamma}_u$ can be realized if $U'_{u,m}$ becomes flatter. This corresponds to choosing a small value of α_m. It should be noted that a similar utility function was proposed in [10] for a distributed power control scheme in wireless cellular systems. Maximization of the utility function there finds the optimum value of the transmission power of each user. In our work, we adopt a similar utility function form in order to calculate the optimal values for the cancellation coefficients and thereby allow proper selection of the interfering signals to be cancelled.

The function $U_{m,u}$ captures the QoS offered to user u. It is obvious that, by maximizing the utility function $U_{m,u}$, the MUE is increasingly satisfied by the received QoS. However, the cost function C_u increases by maximizing the utility function. The resulting net utility function is expressed as follows:

$$U_{net,u}(\gamma_u) = \frac{1}{1+\exp(-\alpha_m\gamma_u)} - \beta_m\gamma_u \quad (9)$$

where β_m corresponds to the parameter β of the MUE.

Consequently, using the analytical form of $\hat{\gamma}_u$ in [11], we express the cancellation coefficients $a_{u,j,r}\,(j \in J_u)$ of the MUE u as follows:

$$a_{u,j,r} = \frac{1}{\jmath_u P_{u,j,r}}\left[-\frac{\alpha_m\, P_{u,i(u),r}}{\ln(\frac{\alpha_m}{2\beta_m}-1-\sqrt{(\frac{\alpha_m}{2\beta_m}-1)^2-1})} - \sigma_{u,r}\right]. \quad (10)$$

However, two necessary conditions must be verified in eq. (10). First, we have to verify that $\left(\frac{\alpha_m}{2\beta_m}-1\right)^2-1 \geq 0$. In order to respect this condition, we must define the parameters α_m and β_m with $\alpha_m \geq 4\beta_m$. Furthermore, the second condition requires that $\frac{\alpha_m}{2\beta_m}-1-\sqrt{\left(\frac{\alpha_m}{2\beta_m}-1\right)^2-1} > 0$, which is verified for $\alpha_m > 4\beta_m$. In conclusion, we must minimize as much as possible the parameter α_m to maximize $\hat{\gamma}_{u,r}$ while respecting the condition $\alpha_m > 4\beta_m$. Thus, we fix $\alpha_m = 4.5\,\beta_m$. Then, we aim to minimize the value of β_m that maximizes the total network throughput while enhancing the user's experience.

B. FUE utility function and IC coefficient

Similar to the MUE, for each FUE $u \in \mathcal{L}_f$, the set of FUEs, we define the following utility function $U_{f,u}$:

$$U_{f,u}(\gamma_u) = W\,log\,(1+\gamma_u) \quad (11)$$

where W denotes the system's bandwidth. This utility function captures the Shannon capacity for the FUE. The resulting net utility function to maximize is expressed as follows:

$$U_{net,u}(\gamma_u) = W\,log\,(1+\gamma_u) - \beta_f\gamma_u \quad (12)$$

where β_f corresponds to the parameter β of the FUE. By maximizing the net utility function $U_{net,u}$, the FUE attempts to enhance its throughput, taking into account the incurred price. Using this utility function and eq. (7), we express the coefficients $a_{u,j,r}$ $(j \in J_u)$ for a FUE $u \in \mathcal{L}_f$ as follows:

$$a_{u,j,r} = \frac{1}{\jmath_u P_{u,j,r}}\left[\frac{\beta_f}{W-\beta_f}P_{u,i(u),r} - \sigma_{u,r}\right]. \quad (13)$$

The proposed DL-IC strategy is summarized in Table I.

Table I
SUMMARY OF DL-IC STRATEGY

For each TTI
  For each RB r
    1- Each user $u \in \mathcal{L}$ measures $P_{u,i(u),r}$, $P_{u,j,r}$ for $j \in J_u$ and $\sigma_{u,r}$.
    2- If
      a- MUE : computes the coefficients $a_{u,j,r}$ $(j \in J_u)$ using eq. (10)
      b- FUE : computes the coefficients $a_{u,j,r}$ $(j \in J_u)$ using eq. (13)
    3- The user computes the post-IC SINR using eq. (3)
  end
end

C. Implementation issues

The DL-IC strategy proposed in this paper requires a limited amount of measurement reports exchange. In fact, the UE and its serving cell cooperate to build the neighboring cells list, and estimate the path loss between it and its neighboring cells. Moreover, the MUE and its serving macro cell exchange measurement reports to update the list of neighboring cells. The UE receiver is then able to estimate the channel gain exploiting the pilot channels received from these cells and compute the received power from them. However, in the case of FUE, the serving femtocell requires an additional DL receiver to measure the signal from the surrounding base stations. This receiver is called "HeNB sniffer". The femtocell uses this receiver to measure the co-channel reference signal received power (RSRP) to determine the coverage of surrounding cells. The RSRPs of surrounding base stations are measured also by the FUE and reported to the serving femtocell. Else, the femtocell measures the reference signal transmission power (RSTP) of neighboring cells and estimates the path loss from attached FUE to the neighboring macrocells and femtocells.

Furthermore, the cancellation process is more and more complex by increasing the number of interfering signals to cancel, called cancellation constraints. In fact, the number of cancellation constraints reflects the implementation complexity of the proposed strategy. Hence, to further limit the computational cost increase in additional support to the effect to the proposed utility functions, we set an upper bound that restricts the number of cancellation constraints. Indeed, the cancellation process is not applied for interfering signals corresponding to cancellation coefficients superior to a pre-defined upper bound, denoted A_u (i.e., if $a_{u,j,r} > A_u$, $a_{u,j,r} = 1$). Likewise, we define a second strategy of cancellation constraints selection. This strategy consists simply in cancelling a pre-fixed number, N_c, of interfering signals having the lowest cancellation coefficients. Consequently, the UE cancels at most N_c received interfering signals. Then, our DL-IC strategy's performance and complexity will both depend on N_c. Furthermore, we define a lower bound, denoted A_l, that reflects the cancellation precision. 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

Table II
SIMULATION PARAMETERS

Parameters	**Macrocell**	**Femtocell**
System frequency	2 GHz	
System bandwith	5 MHz (shared)	
Cell layout	hexagonal grid of 7 cells, 3 sectors per cell	circular cell, 1 sector per cell
Cell size	250 m	20
Antenna gain pattern	TS 36.942	Omnidirectional
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 number of UEs	25 UEs	1 UE
UEs speed	30 Km/h	3 Km/h
Schedular	Proportional fair	
Simulation time in TTIs	1000	
Proposed DL-IC strategy parameters	$\alpha_m = 4.5\,\beta_m$	$W = 5$ MHz $\beta_f = 10^4$ [11]

the minimum value that a cancellation coefficient can take [i.e., $a_{u,j,r} = \max(A_l, a_{u,j,r})$].

IV. SIMULATION RESULTS AND ANALYSIS

In order to evaluate the efficiency of the proposed DL-IC strategy and its impact on network and user performances, we used an LTE network system-level simulator. This simulator generates an area of interest (ROI) composed by 7 hexagonal macrocells. Depending on the simulation scenario, it randomly populates this ROI by femtocell sites up to a requested number of femtocells per macrocell on average. 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 II.

We have earlier mentioned that the performance of the DL-IC strategy depends on its tuning, mainly the parameter β_m. In Fig. 1, we simulate the network performance and plot throughput gains for different values of β_m. The obtained results confirm what has been analyzed analytically in section III. In fact, the smaller is the parameter β_m, more significant is the obtained throughput gain. However, this gain cannot be limitlessly enhanced. Actually, simulation results suggest a throughput gain saturation for values of β_m lower than 10^{-3}. Hence, we set in the following simulations the parameter β_m to 10^{-3}. Results of Fig. 1 suggest that throughput gains against a homogenous network witout IC are as much as 200% plus an extra 98% per additional femtocell site.

As mentionned previously in section III, IC implementation is complex in practice. Thus, we simulate the throughput gains for different values of the upper bound A_u. By reducing the

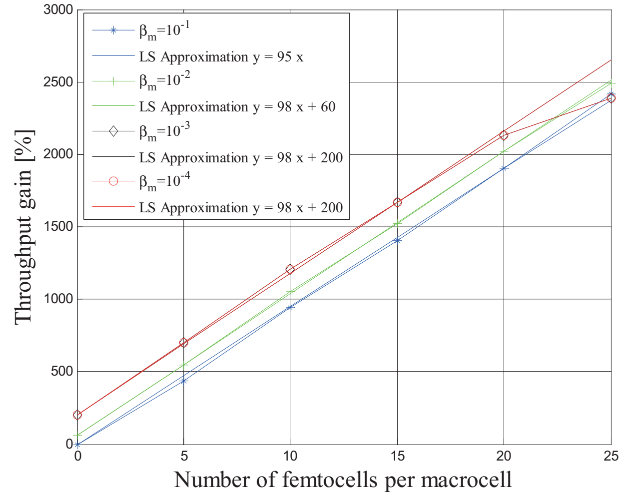

Figure 1. Network throughput gains for different values of β_m ($A_u = 1$; $A_l = 0$).

value of A_u, we reduce the number of interfering signals selected for IC thereby reducing implementation complexity. In Fig. 2, we plot the CDF function of the number of interfering signals to be cancelled for different values of A_u to confirm that the number of cancellation constraints indeed reduces with lower values of A_u. Results of Fig. 3 suggest that as long as A_u is larger than 10^{-2}, there is no performance deterioration compared to perfect IC ($A_u = 1$). For $A_u = 10^{-2}$, the throughput gains against a homogenous LTE network without IC are very significant in the range of 133% plus an extra 85% per additional femtocell site. Compared to a basic HetNet without IC, these gains are still very promising in the range of 133% plus an extra 35% per additional femtocell site. Hence, we set in following simulations the value of A_u to 10^{-2}.

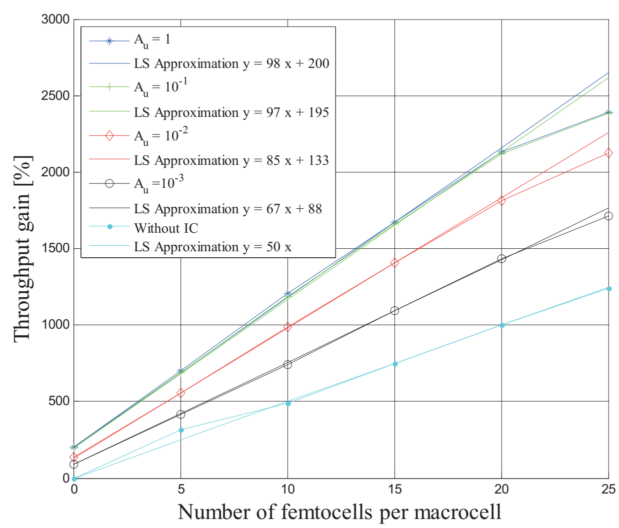

Figure 3. Network throughput gains against a homogeneous LTE network for different values of A_u ($\beta_m = 10^{-3}$; $A_l = 0$).

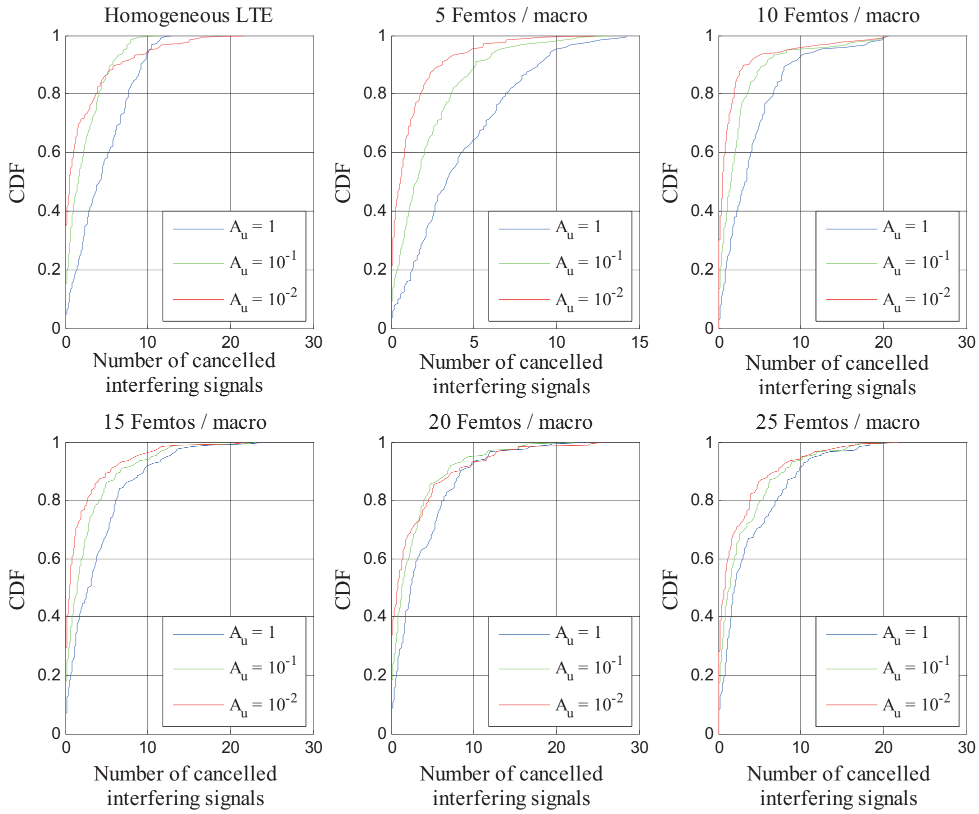

Figure 2. CDF of the number of cancelled interfering signals for different numbers of femtos and different values of A_u.

In Fig. 4, we plot now the throughput gain curves for different values of A_l which reprensents the lowest cancellation ratio due to practical imperfections of IC implementation. They suggest that setting in the following simulations A_l to a maximum practical IC ratio value of 10^{-2} (i.e., -20 dB) results in quite significant throughput gains against a homogenous LTE network without IC, i.e., in the range of 166% plus an extra 78% per additional femtocell site. Compared to a basic HetNet without IC, these gains are still high in the range of 166% plus an extra 28% per additional femtocell site.

In Fig. 5, we evaluate the impact of selecting a fixed number (N_c) of interfering signals to be cancelled on the proposed DL-IC strategy and hence plot the throughput gains for different values of N_c. Results there suggest that limiting the proposed DL-IC to only $N_c = 4$ interfering signals having the lowest cancellation coefficients or ratios results in throughput gains against an LTE homogenous network without IC in the range of 150% plus an extra 70% per additional femtocell site. Compared to a basic HetNet without IC, these gains are still high in the range of 150% plus an extra 20% per additional femtocell site.

In order to further evaluate our DL-IC strategy, now that the proposed DL-IC strategy has been optimized both in throughput performance and implementation cost against a basic HetNet setting without IC, we consider as a benchmark for performance comparisons, the dynamic DL power control

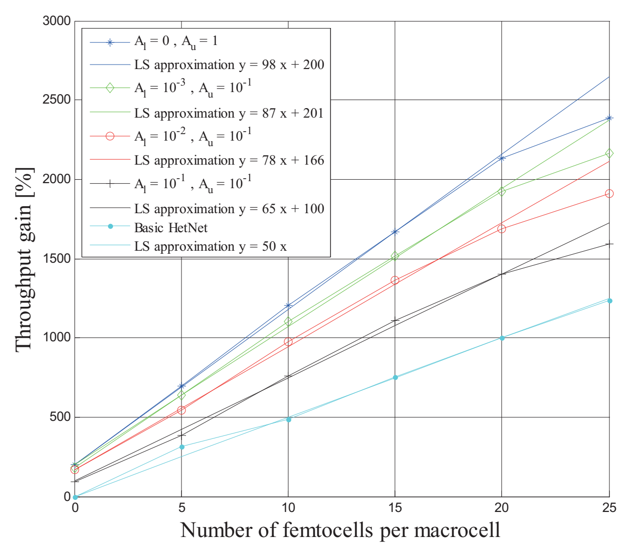

Figure 4. Network throughput gains against a homogeneous LTE network for different values of A_l ($\beta_m = 10^{-3}$).

(DL-PC) algorithm for LTE HetNet proposed in [12]. This algorithm aims to reduce interference impact on the users' received SINR by adjusting the transmission power of femtocells

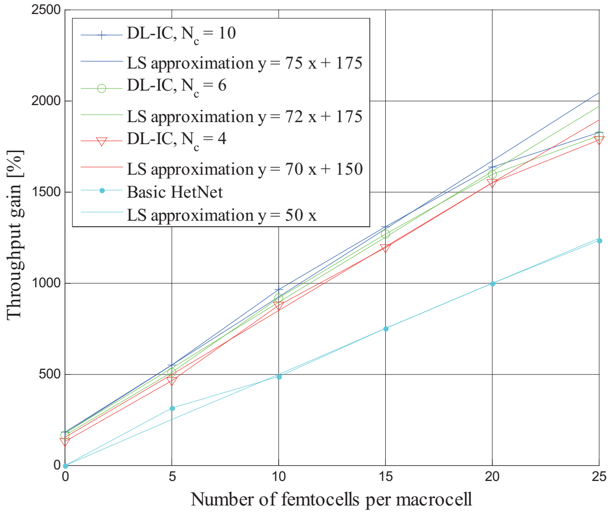

Figure 5. Network throughput gains against a homogeneous LTE network for different values of N_c ($\beta_m = 10^{-3}$; $A_l = 10^{-2}$).

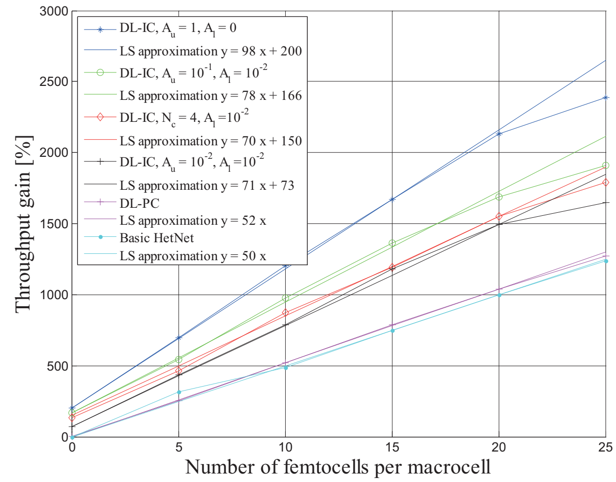

Figure 7. Network throughput gains against a homogeneous LTE network ($\beta_m = 10^{-3}$).

to a level comprised between a minimum transmission power P_{min} and a maxmimum transmission power P_{max}. The basic concept of the dynamic DL-PC algorithm is summarized as follows [12]:

$$P_{DL} \;=\; max\,(P_{min}\;,\; min\,(P_{max}\;,\; P_0 + P_{offset})) \qquad (14)$$

where P_{DL} denotes the transmission power of the femtocell, P_0 represents the received interference measured by the FUE attached to this femtocell and P_{offset} is based on the pathloss between this femtocell and its attached FUE [12]. The values of P_{min} and P_{max} are set, respectively, to -10 dBm and 20 dBm.

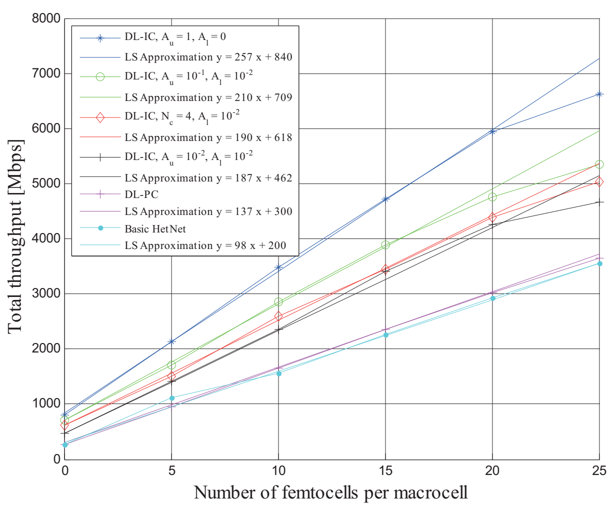

Figure 6. Total network throughputs ($\beta_m = 10^{-3}$).

In Fig. 6, we plot the total network throughputs achieved by our DL-IC strategy (with different setups) and by DL-PC [12] and translate them in throughout gains in Fig. 7. We observe that DL-PC offers only a modest throughput gain of about 2% per additional femocell site against basic HetNet. 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.

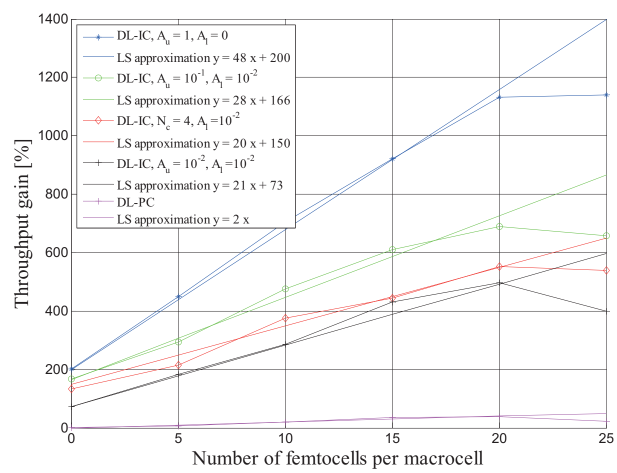

Figure 8. Network throughput gains against a basic LTE HetNet without IC ($\beta_m = 10^{-3}$).

V. Conclusions

In this paper we proposed a shared-spectrum DL-IC strategy that permits an LTE HetNet receiver to eliminate the most severe interference received from neighboring cells, both macro and femto. The propo sed strategy is based on utility functions not yet exploited for IC in HetNet, to the best of our knowledge. These functions permit to relax cancellation coefficients in order to reduce the implementation complexity and compute the optimal cancellation coefficients values for each interfering signal in order to enhance SINR, QoS and throughput. We prove by system-level simulations that the suggested shared-spectrum DL-IC strategy is able to improve the LTE HetNet network throughput and to enhance the users' received SINRs. In fact, throughput gains achievable by the new shared-spectrum DL-IC strategy can reach as much as 200% against a homogeneous LTE network without IC along with an extra 48% per additional femtocell base station in a basic LTE HetNet without IC.

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