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RESEARCH ARTICLE

Throughput and cost-efficient interference cancelation strategies for the downlink of spectrum-sharing Long Term Evolution heterogeneous networks

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ABSTRACT

In a heterogeneous network (HetNet), small cells such as femtocells considered in this work are deployed jointly with macrocells. This new cells' layer, when added to the network, generates interference, which could 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 cancelation (DL-IC) strategy for spectrum-sharing Long Term Evolution (LTE) 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 cancelation 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 throughput, 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 against a basic spectrum-sharing LTE HetNet without IC. These performance figures are shown to surpass those achieved by interference avoidance techniques using either power or frequency resource allocation. Copyright © 2014 John Wiley & Sons, Ltd.

KEYWORDS
LTE HetNet; downlink interference; cancelation; resource allocation

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1. INTRODUCTION

Mobile communication systems undergo constant growth in terms of number of subscribers. In fact, the ITU organization confirms that by the end of 2011, the number of mobile service subscribers reached six billions around the world, with a penetration factor of 86% [1]. In addition, these users require increasingly better quality of service (QoS) and a wide coverage characterized by a strong signal, specifically in low-coverage areas. To cope with these challenges, the new concept of a heterogeneous network (HetNet) was adopted. In HetNet, the network integrates small coverage cells such as femtocells (considered here for illustration purposes and without loss of generality), picocells, or microcells, in conjunction with the existing macrocells. This new cells' layer has been adopted by many wireless communication systems to increase their capacity, maintain their coverage, and meet the 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, intense 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 downlink (DL) interference mitigation in LTE HetNet along different approaches. These are mainly categorized into interference cancelation (typically at the receiver) and interference avoidance (typically at the transmitter) techniques. 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 HetNet were discussed in [4] and [5], mainly by splitting available resources between macrocells and femtocells (or small cells in general) in the time-frequency grid. Because bandwidth is shared between macrocells and femtocells, a properly devised splitting policy can overcome the resource sharing challenges [6].

Frequency reuse, for instance, allows an efficient spectrum sharing between base stations, especially for fully loaded deployments where some regions of coverage will experience high interference levels because of the *ad hoc* distribution of femtocells. 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. FFR thereby increases the signal to interference plus noise ratio (SINR), but reduces the achievable throughput over the entire network by preventing exploitation of the full spectrum. To overcome this gap, adaptive FFR was adopted in several works [6] 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.

Among interference avoidance techniques, power control (PC) algorithms were also widely developed in order to optimize base stations' transmission powers in HetNet, for example, in [7] and [8], so as to reduce interference. More recently, interference alignment was developed as one combination of both interference mitigation categories, that is, avoidance and cancelation, to simplify interference suppression at the UE receivers owing to some coordination between multiple transmitters that is able to align mutual interference at the receivers. As one example, Dao *et al*. [9] proposed an interference alignment technique that aims to mitigate DL interference in cellular networks. In the interference cancelation category, an interference rejection combining (IRC) receiver was proposed in [10] to perform spatial suppression of interfering signals. This work 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 spectrum-sharing downlink interference cancelation (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's intensive computing 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% throughput gain against a homogeneous LTE network without IC along with an extra 48% per additional femtocell base station against a basic LTE HetNet without IC. These performance figures are shown to surpass those achieved by interference avoidance techniques using either power or frequency resource allocation.

The rest of the paper is organized as follows. We discuss in the next section our system model. In Section 3, we develop the proposed spectrum-sharing DL-IC strategy. In Section 4, we confirm by simulations the significant gains achieved in terms of SINR and throughput for both macro-user equipment (MUEs) and femto-user equipment (FUEs).

2. SYSTEM MODEL

We consider a spectrum-sharing two-layer 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, 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

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

3. PROPOSED SPECTRUM-SHARING DOWNLINK INTERFERENCE CANCELATION 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 cancelation 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 cancelation coefficients to be determined. Therefore, the post-IC SINR (i.e., resulting SINR after the IC strategy is implemented) is given 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 spectrum-sharing DL-IC strategy is to compute the optimal cancelation 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 canceled 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 computational cost incurred. The resulting total utility 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 cancelation process with reduced implementation errors. Indeed, perfect cancelation (i.e., $a_{u,j,r} = 0$ ($j \in J_u$)) cannot be realized in practice. Even more, very accurate interference cancelation 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 cancelation 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 Equation (5) and take the derivative of Equation (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 Equations (3) and (6), the cancelation 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 Equation (7), we have assumed the received powers from interfering cells, $P_{u,j,r}$, for any j, to be equal to ease the tractability of Equation (3). This assumption holds when accounting for the averaged received interfering powers over all UE positions. The solution in Equation (7) is then obtained by ultimately substituting the identical averages by their instantaneous realizations obtained at a given UE position. This reasonable approximation simplifies the resolution of Equation (3) and proves later by simulations to be extremely efficient. In the following, we define the utility functions of both the MUE and the FUE.

3.1. Macro-user equipment utility function and interference cancelation coefficients

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 [11]:

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

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 [11] for a distributed PC 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 cancelation coefficients and thereby allow proper selection of the interfering signals to be canceled.

The function $U_{m,u}$ captures the QoS offered to user u. By maximizing the utility function $U_{m,u}$, it is obvious that 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:

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

where β_m corresponds to the parameter β of the MUE. Consequently, using the analytical form of $\hat{\gamma}_u$ in Equation (3), we express the cancelation coefficients $a_{u,j,r}$ $(j \in J_u)$ of the MUE u as follows:

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

However, two necessary conditions must be verified in Equation (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 $\alpha_m > 4\beta_m$. To do so, we have simulated the system for different values of α_m, that is, $\alpha_m = 4.1\beta_m, 4.2\beta_m, \ldots 4.5\beta_m$, and so on. We have then noticed that performance improvements saturate beyond $\alpha_m = 4.5\beta_m$. Hence, we chose $\alpha_m = 4.5\beta_m$ then reduced the value of β_m so as to maximize the total network throughput while enhancing the user's experience.

Table I. Summary of downlink interference cancelation 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 Equation (10)
b- FUE: computes the coefficients $a_{u,j,r}$ $(j \in J_u)$ using Equation (13)
3- The user computes the post-IC SINR using Equation (3)
End
End

RB, resource block; MUE, macro-user equipment; FUE, femto-user equipment.

3.2. Femto-user equipment utility function and interference cancelation coefficients

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

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

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:

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

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 computational price. Using this utility function and Equation (7), we express the coefficients $a_{u,j,r}$ $(j \in J_u)$ for a FUE $u \in \mathcal{L}_f$ as follows:

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

Based on the IC coefficients obtained for the MUEs and FUEs in Equations (10) and (13), respectively, the proposed DL-IC strategy is summarized in Table I.

3.3. 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 macrocell exchange measurement report to update the list of neighboring cells. The UE receiver is then able to estimate the channel gains 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" [12]. The femtocell uses this receiver to measure the co-channel reference signal received power to determine the coverage of surrounding cells. The reference signal received powers 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 of neighboring cells and estimates the path loss from the attached FUE to the neighboring macrocells and femtocells.

Furthermore, the cancelation process becomes increasingly complex when selecting a larger number of interfering signals to cancel, called cancelation constraints. In fact, the number of cancelation 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 cancelation constraints. Indeed, the cancelation process is not applied for interfering signals corresponding to cancelation 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 cancelation constraints selection. This strategy consists simply in canceling a prefixed number, N_c, of interfering signals having the lowest cancelation coefficients. Consequently, the UE cancels at most N_c received interfering signals having the lowest IC coefficients $a_{u,j,r}$. 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 cancelation precision. In fact, imperfections due to channel estimation and signals' reconstruction make it impossible to perform a perfect cancelation of the interfering signals at the requested cancelation ratio or coefficient $a_{u,j,r}$. Therefore, A_l represents the minimum suppression ratio achievable because of IC implementation imperfections or the minimum value that a cancelation coefficient can take [i.e., $a_{u,j,r} = \max(A_l, a_{u,j,r})$]. By choosing larger values of A_l, we reduce not only IC precision but also computational cost as well.

Table II. 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 seven cells, three sectors per cell	Circular cell, one 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	9 dB
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	$\alpha_m = 4.5\,\beta_m$	$W = 5$ MHz $\beta_f = 10^4$ [13]

RBs, resource blocks; UE, user equipment; TTI, transmission time interval; DL-IC, downlink interference cancelation.

4. SIMULATION RESULTS AND ANALYSIS

To evaluate DL-IC strategy and see its impact on network and user performances, we used an LTE network system-level simulator. This simulator generates an area of interest composed by seven hexagonal macrocells. Depending on the simulation scenario, it randomly populates this area of interest 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 II.

4.1. Optimization of downlink interference cancelation's setup for increased throughput and reduced complexity

We have aforementioned that the performance of the DL-IC strategy depends on its tuning, mainly the parameter β_m. In Figure 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 3. 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 Figure 1 suggest that throughput gains against a homogenous network without IC are as much as 200% plus an extra 98% per additional femtocell site. Please note that LS, in the figures' legend, refers to the conventional least squares linear regression. We recurred to the LS fit of each throughput curve in the figures knowing well in advance that the expected throughput gain behavior with the number of femtocells increasing should be about linear. The new results obtained here confirm that this linear behavior holds until a relatively large number of femtocells.

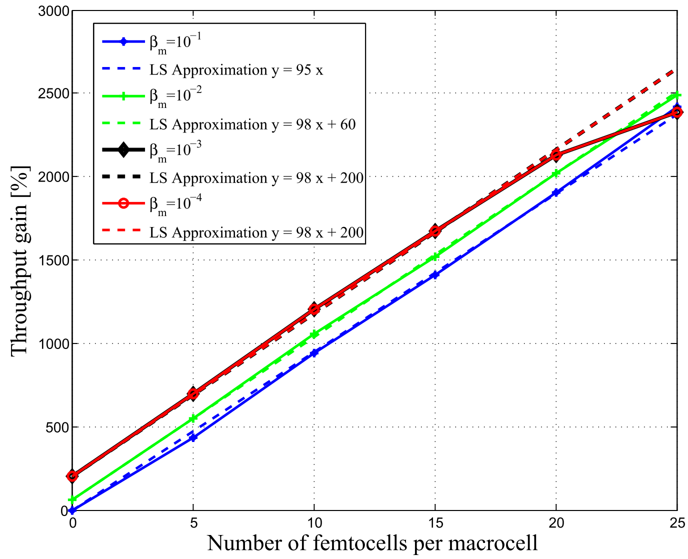

Figure 1. Network throughput gains against a homogeneous Long Term Evolution network for different values of β_m ($A_u = 1$; $A_l = 0$).

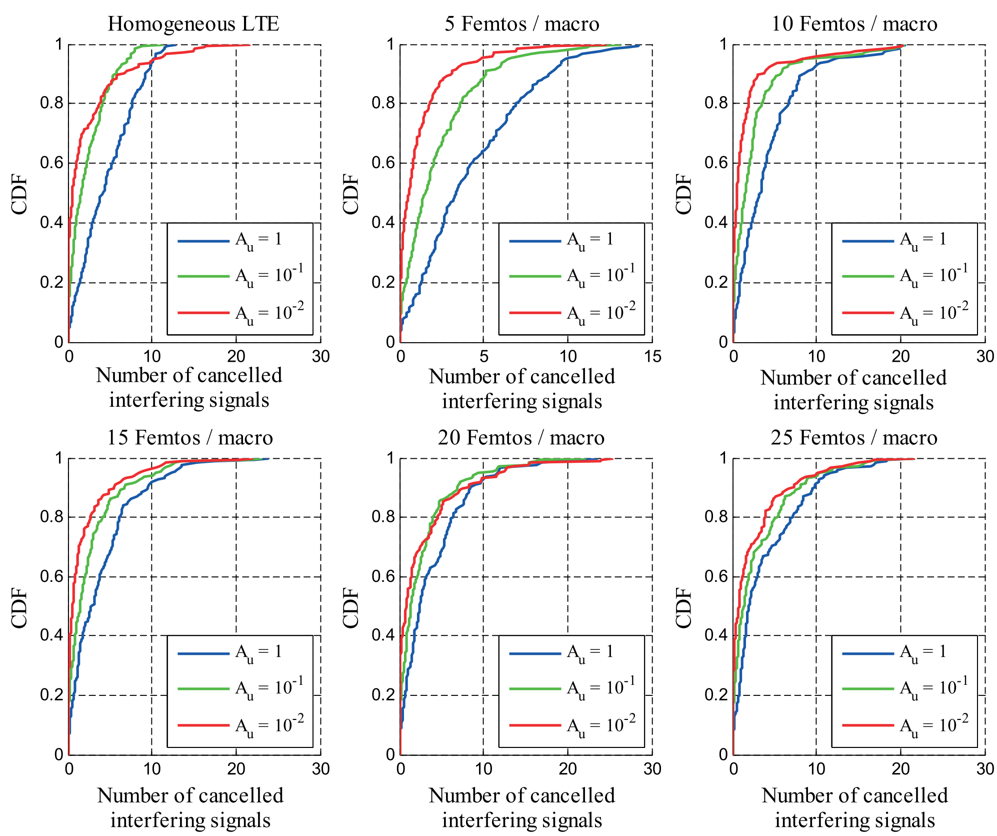

Figure 2. CDF of the number of canceled interfering signals for different numbers of femtos and different values of A_u.

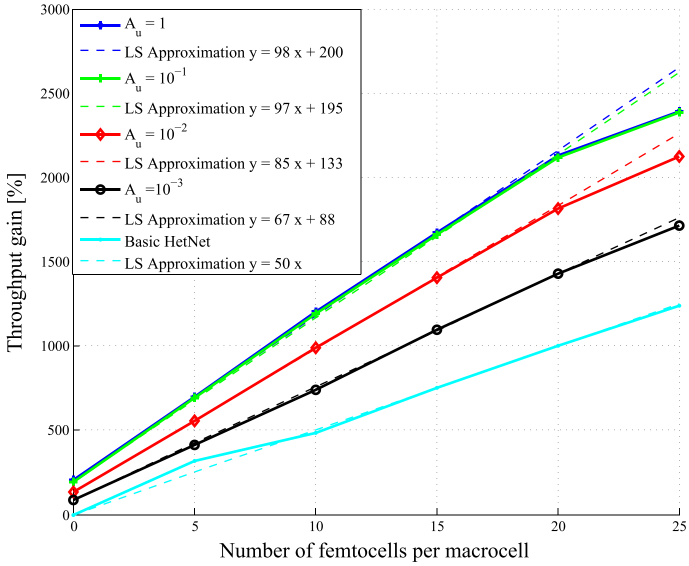

Figure 3. Network throughput gains against a homogeneous Long Term Evolution network for different values of A_u ($\beta_m = 10^{-3}$; $A_l = 0$).

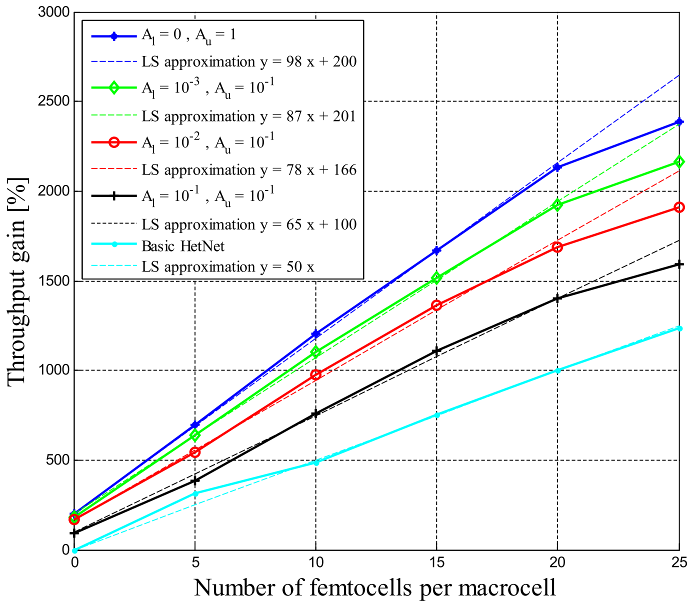

Figure 4. Network throughput gains against a homogeneous Long Term Evolution network for different values of A_l ($\beta_m = 10^{-3}$).

As mentioned previously in Section 3, IC implementation is complex in practice. Thus, we simulate the throughput gains for different values of the upper bound A_u. By reducing the value of A_u, we reduce the number of interfering signals selected for IC thereby reducing implementation complexity. In Figure 2, we plot the cumulative distribution function (CDF) of the number of interfering signals to be canceled for different values of A_u to confirm that the number of cancelation constraints indeed reduces with lower values of A_u. We notice that when the number of femtocells increases, the number of cancelation constraints still reduces with lower values of A_u. However, the variation is less sensitive to the values of A_u than that for smaller femtocells' number. Results of Figure 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

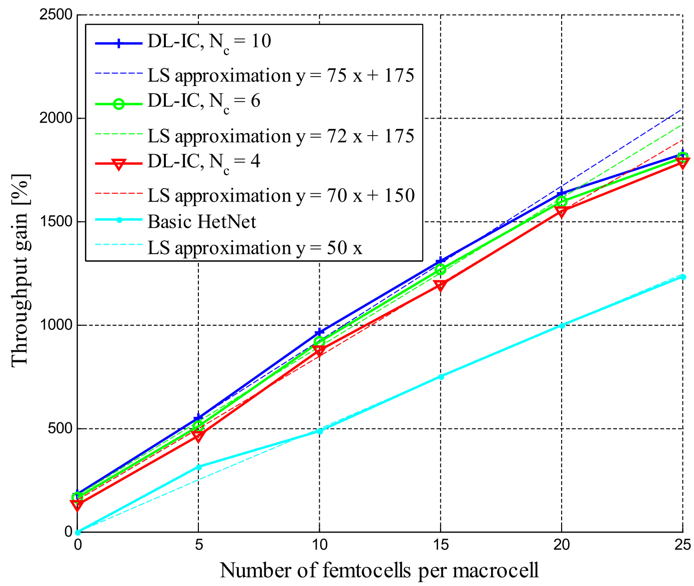

Figure 5. Network throughput gains against a homogeneous Long Term Evolution network for different values of N_c ($\beta_m = 10^{-3}$; $A_l = 10^{-2}$).

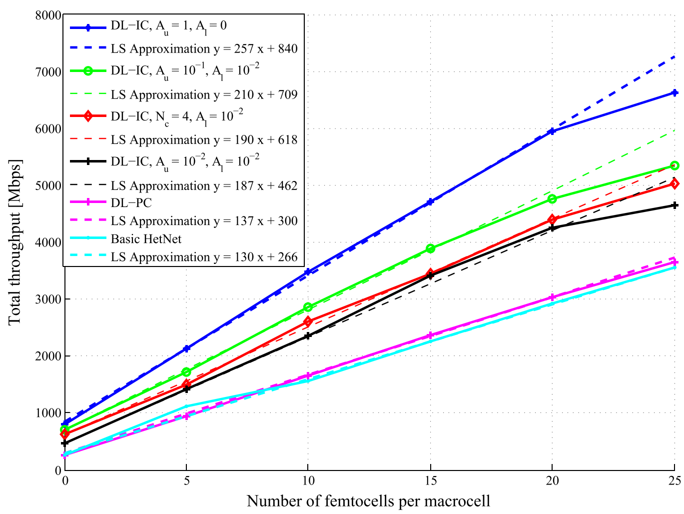

Figure 6. Total network throughputs ($\beta_m = 10^{-3}$).

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}.

In Figure 4, we plot now the throughput gain curves for different values of A_l, which represents the lowest cancelation ratio because of 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, that is, 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 Figure 5, we evaluate the impact of selecting a fixed number (N_c) of interfering signals to be canceled 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 cancelation 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

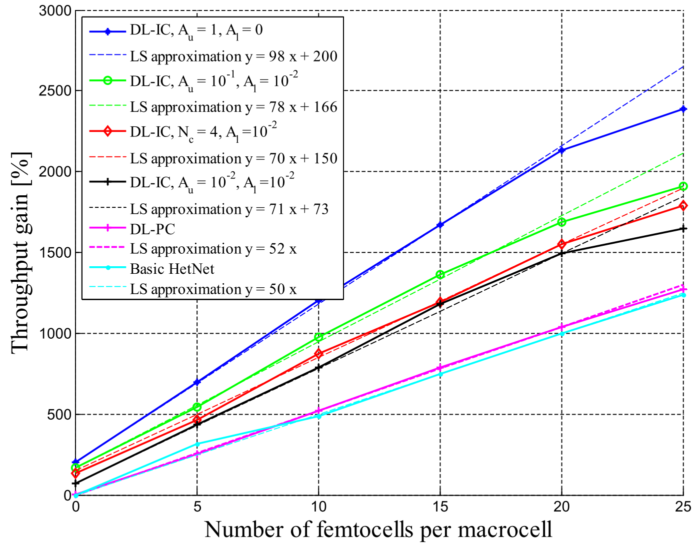

Figure 7. Network throughput gains against a homogeneous Long Term Evolution network ($\beta_m = 10^{-3}$).

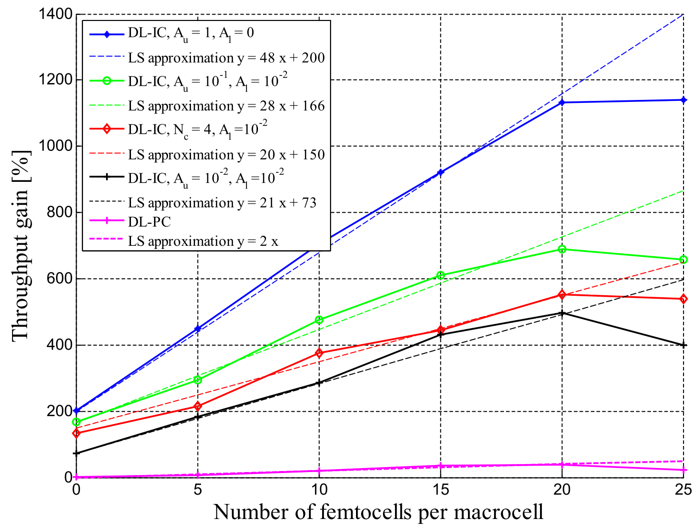

Figure 8. Network throughput gains against a basic Long Term Evolution heterogeneous network without IC ($\beta_m = 10^{-3}$).

Table III. Signal to interference plus noise ratio based decreasing-order ranking of resource blocks for victim macro-user equipment (MUE).

	Victim MUE index			
RB r	1	2	$\cdots$	K
N	$R_{1,N}$	$R_{2,N}$	$\cdots$	$R_{K,N}$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
2	$R_{1,2}$	$R_{2,2}$	$\cdots$	$R_{K,2}$
1	$R_{1,1}$	$R_{2,1}$	$\cdots$	$R_{K,1}$

RB, resource block.

Table IV. Score per resource block (RB) based on the average of ranking values over victim macro-user equipment in Table III.

RB r	Score
N	$s_N = mean\{\ldots, R_{k,N}, \ldots\}, k \in \{1, .., K\}$
$\vdots$	$\vdots$
$\vdots$	$\vdots$
2	$s_2 = mean\{\ldots, R_{k,2}, \ldots\}, k \in \{1, .., K\}$
1	$s_1 = mean\{\ldots, R_{k,1}, \ldots\}, k \in \{1, .., K\}$

Table V. Allowed and blocked femtocell resource block (RBs).

RB r	RB status
r_N ⋮ r_{B+1}	Allowed
r_B ⋮ r_1	Blocked

the range of 150% plus an extra 20% per additional femtocell site.

4.2. Comparisons against interference avoidance techniques through power control

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 first benchmark for performance comparisons, the dynamic DL-PC algorithm for LTE HetNet proposed in [14]. This algorithm aims to reduce interference impact on the users' received SINR by adjusting the transmission power of femtocells to a level comprised between a minimum transmission power P_{min} and a maximum transmission power P_{max}. The basic concept of the dynamic DL-PC algorithm is summarized as follows [14]:

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

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 [14]. The values of P_{min} and P_{max} are set, respectively, to -10 dBm and 20 dBm.

In Figure 6, we plot the total network throughput achieved by our DL-IC strategy (with different setups) and by DL-PC [12] and translate them into throughput gains in Figure 7. We observe in Figure 8 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 versus 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 that are of up to 200% against a homogenous network without IC plus an extra 48% per additional femtocell site against basic HetNet without IC.

4.3. Comparisons against interference avoidance techniques through frequency partitioning

Here, we consider as a second benchmark for comparisons the conventional FFR discussed in [15], without PC on femtocell subbands. Accordingly, we divide the available resources into four subbands f_0, f_1, f_2 and f_3 split between the cell center and the edges of the three sectors, respectively. A femto-user placed in the cell center can use f_1, f_2, and f_3, a femto edge-user placed in sector l uses the subbands $\{f_p\}$, where $p \neq l$.

As a third benchmark, we propose an adaptive subband allocation (ASA) scheme where macrocells use the entire spectrum and femtocells exploit only a fraction of all resources. In this strategy, macro-users are classified into safe users and victim users according to the received interference from the corresponding femtocell. For each victim MUE, served by the femtocell's parent macrocell, and given an index k among 1 to K where K denotes the

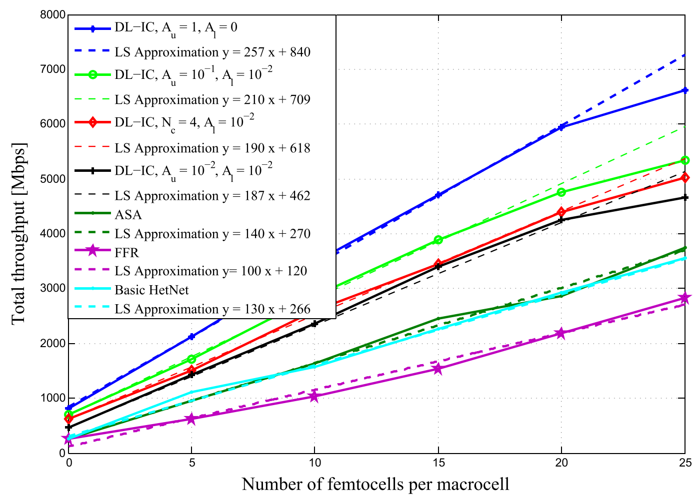

Figure 9. Total network throughputs ($\beta_m = 10^{-3}$).

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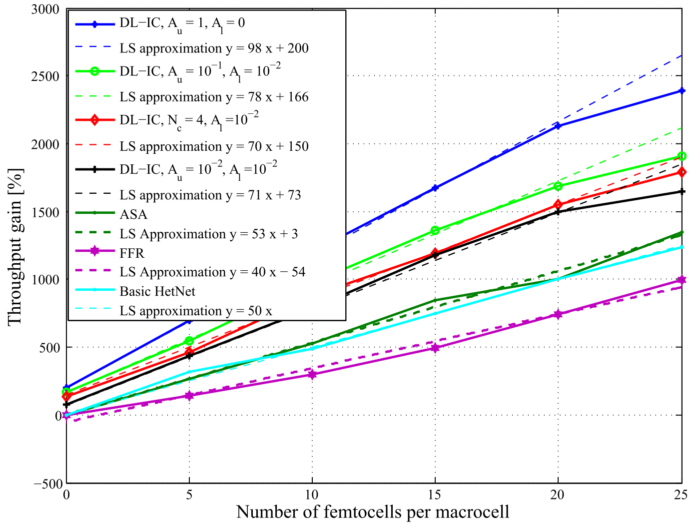

Figure 10. Total network throughput gains against a homogeneous Long Term Evolution network ($\beta_m = 10^{-3}$).

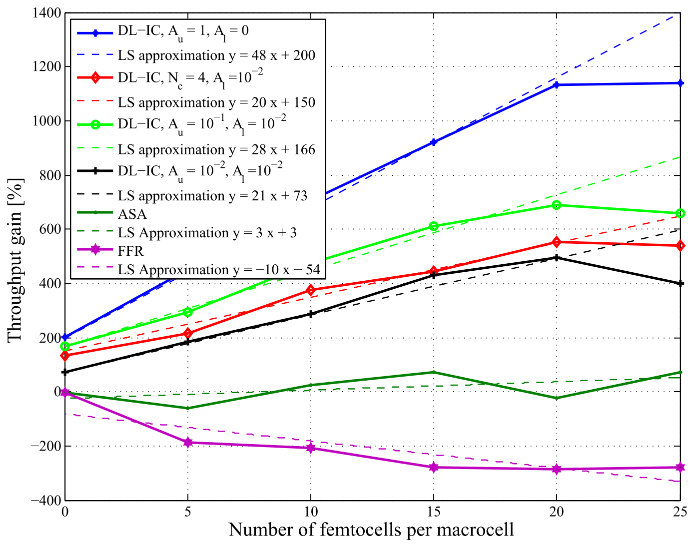

Figure 11. Network throughput gains against a basic Long Term Evolution heterogeneous network without IC ($\beta_m = 10^{-3}$).

identified number of victim MUEs, we attribute for each of its RBs $r = 1, \ldots, N$ a decreasing-order SINR-based ranking value $R_{r,k}$ among 1 to N, as illustrated in Table III. For each RB index r, we then define in Table IV a corresponding score s_r as the average of the ranking values over victim users given in Table III. In Table V, we ultimately rank the RBs in a decreasing order based on the scores s_r obtained in Table IV (i.e., $s_{r_m} < s_{r_{m+1}}$ where r_m denotes the RB index ranked in Table V)). In [16], a femto free-zone is defined as a given part of the RBs where femtocells are not allowed to transmit. Here, a femtocell is allowed to determine its free-zone characterized by the number B of RBs to be blocked out of N according to the blocking ratio ρ_B as follows:

$$B = \lceil N \times \rho_B \rceil \quad (15)$$

where

$$\rho_B = \frac{K}{N_F + N_M} \quad (16)$$

where N_F and N_M are the numbers of FUEs and MUEs served by the femtocell and its parent macrocell, respectively. The blocked RBs are those having indexes r_1 to r_B at the bottom of Table V, that is, the B indexes of the RBs having the lowest scores s_r obtained in Table IV.

For each femtocell, the allowed RBs identified in Table V are fed to a proportional fair scheduler to be distributed among served FUEs.

In Figure 9, we plot again the total network throughput achieved by our DL-IC strategy (with different setups) and by both FFR and ASA described earlier, and translate them into throughput gains in Figure 10. Taking basic HetNet as a reference against which throughput performance is gaged, we observe in Figure 11 that FFR suffers from throughput losses (because of its rigid frequency partitioning briefly discussed earlier) while ASA offers only a modest throughput gain of about 3% per additional femtocell site.

5. CONCLUSIONS

In this paper, we proposed a spectrum-sharing DL-IC strategy that permits an LTE HetNet receiver to eliminate the most severe interference received from neighboring cells, both macrocells and femtocells. The proposed strategy is based on utility functions not yet exploited for IC in HetNet, to the best of our knowledge. These functions permit to relax cancelation coefficients in order to reduce the implementation complexity and compute the optimal cancelation coefficients values for each interfering signal in order to enhance SINR, QoS, and throughput. We prove by system-level simulations that the suggested spectrum-sharing 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 spectrum-sharing DL-IC strategy can reach as much as 200% throughput gain against a homogeneous LTE network without IC along with an extra 48% per additional femtocell base station against a basic LTE HetNet without IC. These performance figures are shown to surpass those achieved by interference avoidance techniques using either power or frequency resource allocation.

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