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The Inter-Cell Interference Dilemma in Dense Outdoor Small Cell Deployment

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***Abstract*— The deployment of low-power small cells is envisaged as the main driver to accommodate the mobile broadband traffic growth in cellular networks. Depending on the spatial distribution of the user traffic, a densification of the small cells may be required in confined areas. However, deploying more and more cells in given areas may imply an increase of the inter-cell interference among the small cells. This study aims at investigating if the inter-cell interference among outdoor small cells may represent an impairment to the user experience, and evaluates if and in what conditions the interference coordination is worthwhile compared to the universal frequency reuse. Results show that the inter-cell interference depends on the small cell deployment in the urban environment (e.g. streets and squares) and on the network load condition. In case of deployment along urban streets, the inter-cell interference does not affect the user throughput and no interference coordination is required. On the other hand, if deployed in open areas (e.g. city squares) the interference coordination enhances both average and coverage user throughput in case of high network load condition.**

I. INTRODUCTION

The expected traffic growth in mobile broadband [1] will require operators to upgrade their network capacity in order to maintain high user experience in the coming years. It is recognized that increasing the number of cells is the largest contributor to the network capacity [2]. Due to their high installation cost and complexity, the amount of traditional macro sites is unlikely to increase in an urban scenario. On the other hand, the deployment of heterogeneous networks (HetNets) where low-power small cells assist the traditional macro base stations to provide capacity in areas with high traffic demand, offers a cost efficient solution to cope with the expected traffic increase.

Depending on the spatial distribution of the traffic and the minimum guaranteed user data rate, a densification of small cells in confined areas may be required. However, packing more and more cells within the same area may imply some technical issues such as the increase of the inter-cell interference among the small cells [3]. Thus, this study addresses the inter-cell interference problem among outdoor small cells in a dense urban deployment in order to understand whether the inter-cell interference causes any impairment to the user experience.

In the literature the inter-cell interference management for small cells has been widely discussed. Two types of inter-cell interference are investigated: Between macro and small cells in case of co-channel multi-layer networks, as discussed in [4], and among small cells when those are deployed on a dedicated channel. Examples of how to mitigate the inter-cell interference among indoor small cells can be found in [5] – [7]. The studies introduce automated coordination procedures based on utility functions to switch on and off shared frequency component carriers. The algorithms rely on the channel sensing and the feedbacks sent by the user equipments (UEs) to take either autonomous or cooperative decisions. The results of these studies have shown that the interference coordination is a useful tool to overcome the inter-cell interference and provide gain in user throughput, especially for those users at the cell edge. However in [8] the authors have demonstrated that the interference coordination is worthwhile only in particular indoor environments.

The majority of the studies on the inter-cell interference among small cells in the literature have focused on indoor deployment scenarios. Such scenario is the most challenging from an interference point of view since the installation of the small cells is not always controlled by mobile network and might be completely unplanned. Nevertheless, the inter-cell interference may represent a technical issue also for a dense deployment of planned outdoor small cells. In [9] the authors have proposed a resource sharing method to mitigate the inter-cell interference among outdoor small cells and shown that the interference coordination provides gain in user throughput also in such scenario. However it was not investigated how the urban environment and the network load condition may affect the interference coordination benefits, as demonstrated in [8] for the indoor scenario. Hence, this study aims at addressing the inter-cell interference problem in a dense urban deployment of planned outdoor small cells, and evaluates in which urban environment (e.g. streets, squares) and network load condition the interference coordination is worthwhile compared to the universal frequency reuse.

The investigation is carried out in a Manhattan grid-like scenario in order to assess the inter-cell interference problem in an environment resembling a real urban deployment. For this purpose, the grid has been modified in order to include high traffic hot-zones in open areas, such as city squares. The small cells are regularly placed along the streets and in the open areas, and deployed on a dedicated channel at 3500 MHz with 40 MHz bandwidth. The small cell deployment provides full coverage over the whole simulated area. Thus, no Macro layer is assumed. Unlike most of the studies in the literature where stationary users and constant load condition are assumed, this study investigates the effect of the inter-cell interference on the throughput of users moving in an urban scenario under different network load conditions.

The paper is structured as follows: Section II presents an overview of the scenario and the problem formulation; Section III describes the frequency reuse planning; Section IV describes the simulation assumptions for the results shown in Section V; finally the conclusions are drawn in Section VI.

II. System Model and Problem Formulation

This section describes the chosen urban scenario and introduces the inter-cell interference problem in a dense deployment of outdoor small cells.

A. *Small Cell Dense Deployment Scenario*

In order to assess the inter-cell interference problem in a scenario resembling a real urban environment the study is carried out in a Manhattan grid-like scenario. For this purpose the grid has been modified in order to include open areas (e.g. city squares). The size of the building block is 85x85m and the street width is 15m. The size of the open areas is 115x115m. Furthermore, 60 outdoor Pico cells (i.e. type of small cells) are regularly deployed on lampposts (6m height) along the streets and within the squares with an inter-site distance of 100m. The assumed frequency band is 3500MHz with 40MHz bandwidth. The Pico cells are able to provide full coverage over the whole simulated area. An overview of the deployment is illustrated in Figure 1.

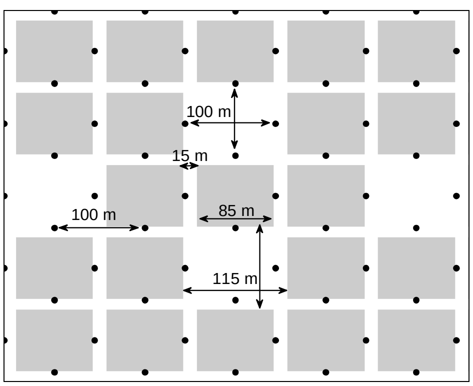

Figure 1. Small cells deployment.

As regards the signal propagation in the city environment, it was assumed that nearby Pico cells deployed along the same street are in Line-of-Sight condition. Similar assumption is assumed for the Pico cells deployed in the same open area. In order to accurately predict the Line-of-Sight and the Non-Line-of-Sight propagation of the signal in the grid, the outdoor path-loss is evaluated by means of a 3D ray-tracing tool based on the dominant path model [10].

B. *Problem Formulation and Objectives*

The densification of the small cells offers a cost efficient solution to provide the needed capacity in given areas with high traffic demand. However as the small cells get closer the inter-cell interference may increase. The increase in interference also depends on how the signal of the small cells propagates in the city environment. Depending on the deployment, e.g. in line along the streets or at the borders of a square, it is likely that no big obstacles are in between of nearby small cells. On condition of Line-of-Sight, the inter-cell interference may increase and degrade the user throughput, in particular for those users at the cell edge.

In order to understand how the deployment plays a role in the inter-cell interference pattern, from the Manhattan-grid it is possible to retrieve information about the UE Signal to Interference plus Noise Ratio (SINR) at the antenna port when full load is assumed. Figure 2 shows the UE SINR versus the distance to the serving cell for UEs connected to a small cell in the street and UEs connected to a small cell in the square. It is possible to observe that the interference within the squares is on average ~5dB higher that in the streets. While moving in between of two buildings the UEs in the streets are shielded from the interference of the nearby small cells in the intersecting streets, whereas no big obstacle is in between the transmitters and the receivers within the open areas. Consequently the inter-cell interference on the squares is higher than in the streets. However, similar SINR is visible for the UEs at the cell edge (~45m) since the number of strong interferers in both street intersection and middle of the square is similar.

Thus, the objective of the study is to investigate the effect of the inter-cell interference on the throughput of users moving in a dense urban deployment of small cells, and to evaluate in which urban environment the interference coordination is worthwhile compared to the universal frequency reuse.

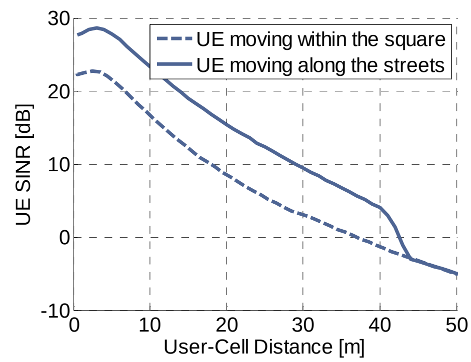

Figure 2. Signal to Interference plus Noise Ratio for users connected to a small cell in the street and a small cell in the square.

III. Interference Coordination

The interference coordination via the frequency reuse is a useful tool to mitigate the inter-cell interference among small cells. The technique consists of splitting the overall available bandwidth into a certain number of orthogonal component carriers and assigning those to each small cell so that nearby small cells transmit on different carriers. Consequently the inter-cell interference is reduced, but at the cost of reduced cell bandwidth.

The interference coordination can be realized statically, i.e. frequency planning, or dynamically based on e.g. autonomous carrier frequency selection by means of Self-Organizing Network (SON) algorithms. In this study an optimized static frequency reuse planning for the Manhattan-grid is considered. The bandwidth is split into either 2 or 4 carriers (i.e. frequency reuse 2 and 4). In the frequency reuse 2 the same carrier is assigned every two Pico cells along the same street, as shown in the example in Figure 3.

In the reuse 4 the assignment has followed two simple rules: the same carrier is assigned every four Pico cells along the same street; each cell facing a common street intersection is assigned to a different carrier. An example of the final deployment is shown in Figure 4.

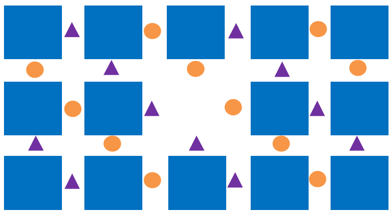

Figure 3. Example of Reuse 2 deployment in Manhattan Grid. Each color represents a different carrier frequency.

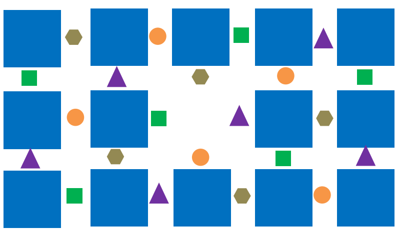

Figure 4. Example of Reuse 4 deployment in Manhattan Grid. Each color represents a different carrier frequency.

IV. SIMULATION ASSUMPTIONS

In order to assess the study on the inter-cell interference problem, system level simulations were performed in the scenario introduced in Section II.A. This section describes the main simulation assumptions.

A. *Scenario Assumptions*

The performance has been assessed with a system level simulator. The chosen radio access technology is the Long Term Evolution-Advanced (LTE-A). Further simulation parameters are listed in Table 1.

Some of the users are initially placed randomly in the streets, and some are confined in 4 hot-spot areas placed within the open areas. The size of the hot-spot is 90x90m. The users move with 3 km/h. Uniform turning probability is assumed when a user in the street reaches the street intersection. The users in the open areas are free to move along straight lines but confined in the hot-spot area. The UE mobility relies on the Reference Signal Received Power (RSRP) measurements for intra and inter-frequency handovers. At the beginning of the simulation the UEs are connected to the cell with the best RSRP.

Time variant bursty traffic is assumed, as described in Table 1. A new packet p_k of fix size S is created per user every t seconds after the user has completed the download of the previous packet p_{k-1}. The inter arrival time t is negatively exponential distributed. The packet inter arrival time is decreased from 12 sec to 1 sec as in Table 1 in order to emulate different offered load conditions (from low load to high load).

B. *User Mobility Assumptions*

A detailed LTE-A user mobility framework for idle and connected mode is modeled. Intra and inter frequency handovers are triggered by the A3 event [11] (target cell is offset better than the serving cell) based on Receive Signal Power (RSRP) measurements. Inter frequency measurements are started by the A2 event [11] (serving RSRP goes below a threshold), and stopped by A1 event (serving RSRP goes above a threshold). Time-to-Trigger [11] for each of the events is also assumed. For the idle mode, cell reselection is performed by R-criterion [11]. In order to trigger idle mode intra-frequency and inter-frequency measurements the serving cell has to fall below respectively S-intraSearch and S-interSearch thresholds.

Table 1. Simulation Parameters.

Number of Cells	60 LTE-A Pico cells @ 3500 MHz, No Macro Layer
Bandwidth	Reuse 1: 40MHz TDD (2 carriers of 20MHz) Reuse 2: 20MHz TDD Reuse 4: 10MHz TDD
Transmission Power	Pico: 30 dBm per carrier
Transmission Mode	2x2 MIMO
Shadowing	No Log-Normal Shadowing
Path Loss Model	3D Ray Tracing: Dominant Path Model LOS decay exponent 2.9 NLOS decay exponent 3.2
User distribution	1500 users moving along the streets; 200 users in hot-spot areas of 90x90m
Measurement Error	Normal Distr. RSRP: 1.21 dB std.
L1 Inter-Frequency Measurements	Connected Mode: 5 ms meas. gap every 40 ms Idle Mode: 5 ms every Discontinous Reception (DRX) cycle (1.2 sec)
L3 Filter Factor	RSRP: 4; L3 filtering as defined in [11]
User Mobility	A3 Offset: 3 dB (Intra-Freq and Inter-Feq A3) A2 threshold: -75 dB; Sinter-freq: -75 dB; Sintra-freq: -75 dB
Time-to-Trigger	Intra frequency: 400 ms Inter frequency: 400 ms
HO execution time	Intra frequency: 150 ms Inter frequency: 500 ms
Radio Link Failure	As defined in [10]
Traffic Model	Fix packet size : 4000 kb; Exp. Distribute packet inter arrival time: [12; 8; 5; 4; 3; 2; 1.2] sec.
Connected to/from Idle mode timing	Idle to Connected mode: 100 ms Release timer Connected to Idle mode: 1 sec

All the UEs are assumed Carrier Aggregation (CA) capable [12]. Hence, the UE is able to aggregate more than one available component carrier frequency in order to receive data on a large bandwidth and achieve high peak data rate.

Since all the UEs are assumed CA capable, in case of universal frequency reuse (reuse 1) the UEs are able to aggregate the two available carriers of 20MHz per Pico cell and receive data on 40MHz overall bandwidth. An ideal CA mobility framework is assumed: The UEs are always configured with two carriers. Thus, when the UE is in connected mode, the secondary cell [12] is immediately configured and activated at the moment of the primary cell [12] change (i.e. handover from serving to target cell). Similar assumption applies for a UE switching from idle to connected mode.

As concerns the frequency reuse 2 and 4 deployment it is worth to recall that nearby Pico cells transmit on different carrier frequencies. From a UE mobility point of view, this means that the UE has to perform inter-frequency measurements in order to detect nearby Pico cells. Thus, A2 and SinterSearch thresholds are set high enough in order to allow the users to measure the closest small cell on a different carrier frequency. If otherwise, the users moving towards a new dominant cell would not be able to connect to it. Consequently the A2 and SinterFreq thresholds have been optimized in order to guarantee the highest UE throughput.

C. Key Performance Indicators

The performance evaluation focuses on the effect of the inter-cell interference on the user throughput. Thus, the following performance indicators (KPIs) are introduced:

- Average UE Session Throughput: average throughput necessary to download a packet of size *S*;
- 5%-ile User Session Throughput: 5%-ile of UE session throughput distribution, i.e. the 5% worst users may achieve equal or lower throughput.

V. Simulation Results

In this section the simulation results are presented for the users moving along the streets and the users in the hot-spots for different network load conditions. The performance evaluation is based on the KPIs described in Section IV.C.

A. Street Users

Figure 5 illustrates the average session throughput of the street users versus the served traffic of the cells deployed along the streets (i.e. average throughput that a cell is able to deliver given a certain offered traffic).The points in the curves are obtained varying the offered load (from low load to high load) as described in Section IV.A.

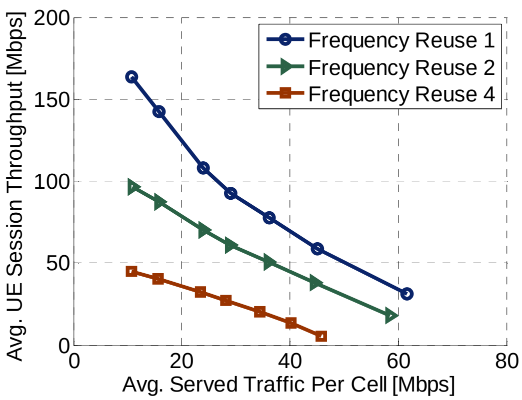

Figure 5. Avg. UE Session Throughput vs. Avg. Served Traffic per Cell for different frequency reuses.

From the results it is possible to observe that the reuse 1 with CA shows the highest average user throughput performance and consequently the highest served traffic. In case of frequency reuse 2 and 4, the session throughput decreases while increasing the frequency reuse ratio. The worst average UE throughput performance is shown by the reuse 4 with a loss of ~73% over the reuse 1 with CA in low load and ~90% in high load. Thus the gain in Signal to Interference plus Noise Ratio (SINR) provided by the frequency reuse 4 over the universal reuse is not sufficient to compensate the loss in bandwidth.

Figure 6 presents the performance in terms of 5%-ile Session Throughput. Similarly to the average user throughput, the reuse 2 and 4 show the worst throughput (~28% and ~64% loss respectively for reuse 2 and 4 compared to reuse 1 in low load; ~65% loss for reuse 4 in high load).

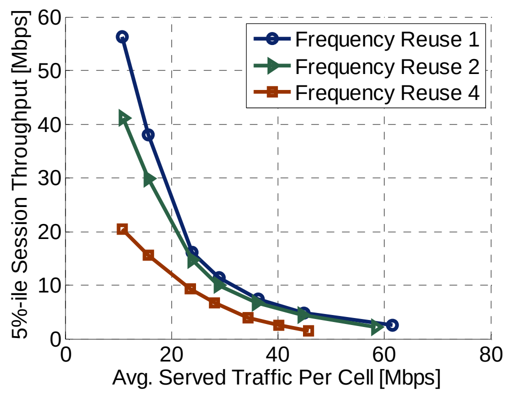

Figure 6. 5%-ile UE Session Throughput vs. Avg. Served Traffic per Cell for different frequency reuses.

B. Hot-Spot Users

The average user throughput for the hot-spot users is presented in Figure 7. Unlike the street users, the reuse 4 shows better performance than the other 2 cases in high offered load conditions with maximum ~200% gain over the reuse 1. A loss of ~70% is however visible in low load compared to the reuse 1 case. In such load condition the CA provides high peak data rate by means of wide spectrum availability and low interference.

Figure 8 shows the 5%-ile user throughput. It is possible to observe that the reuse 4 also achieves gains of maximum ~200% at medium/high load over the reuse 1 with CA.

In order to understand the difference between the user performance in the streets and in the hot-spots, it is important to recall the small cells interference pattern in the city environment. As shown in Section II.A, the inter-cell interference increases for those users in the open areas where more than 1 interferer is visible per each user.

Figure 9 compares the SINR at the antenna port of the street and hot-spot users in case of reuse 1, 2 and 4 in high load condition. From the SINR distribution it is possible to observe that the users in the hot-spot are severely affected by the interference in the case of reuse 1 and reuse 2 (~12 dB difference). Almost no difference is visible in the user SINR in case of reuse 4.

Finally, comparing the street scenario with the hot-spot scenario, note that the system capacity is also affected by the inter-cell interference: Due to stronger interference in the hot-spot, the maximum served traffic of the cells in the open areas is lower than the one in the streets (Figures 5-8).

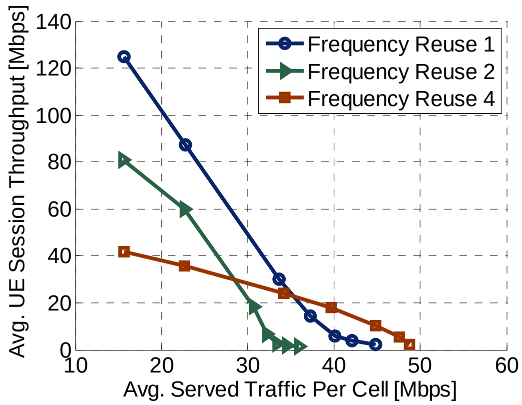

Figure 7. Avg. UE Session Throughput vs. Avg. Served Traffic per Cell for different frequency reuses.

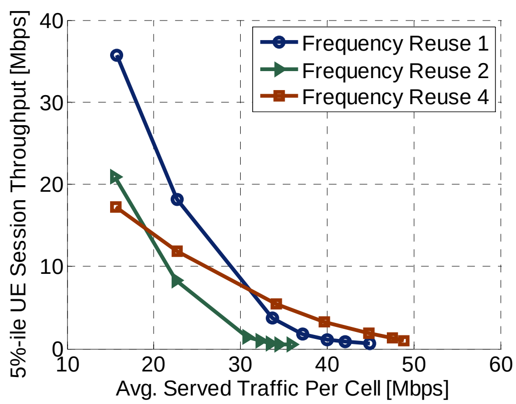

Figure 8. 5%-ile UE Session Throughput vs. Avg. Served Traffic per Cell for different frequency reuses.

VI. CONCLUSIONS

This study aimed at investigating if the inter-cell interference among outdoor small cells may represent an impairment to the user experience in a dense deployment of outdoor small cells, and at evaluating in what conditions the interference coordination is worthwhile compared to the universal frequency reuse in an urban environment.

Simulation results have shown that the benefits of the interference coordination depend on the small cell deployment in the urban environment and the network load condition. In particular, if the small cells are placed along urban streets the user throughput is not severely affected by the inter-cell interference. Thus no interference coordination is needed. When deployed in open areas, such as city squares, the inter-cell interference increases while the network load increases. In such deployment, the interference coordination enhances the average and the coverage user throughput at high load condition with gains up to ~200% compared to universal frequency reuse.

The current study has been performed in a regular deployment of small cells to allow easy fix frequency reuse planning. As a future work, the study should be carried out in a less regular deployment of small cells where the carrier assignment is performed by means of dynamic spectrum allocation.

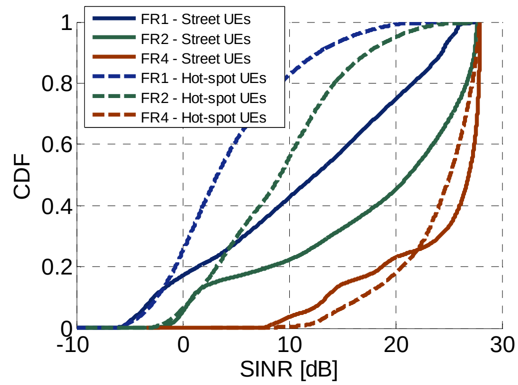

Figure 9. UE SINR at the antenna port of street and hot-spot UEs in connected mode in case of high load condition for frequency reuse 1 (FR 1), 2 (FR 2) and 4 (FR 4).

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