Characterisation of Uplink Other-cell Interference in Co-channel WCDMA Small Cell Networks

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***Abstract*—This paper investigates the effect of the other-cell interference in WCDMA small cell networks when operating on the same frequency channel of the hosting macrocell tier. In this paper, the problem formulation is presented and it is shown that the co-channel interference and the effective capacity can not be analytically traced. Consequently, using simulation and modelling, the paper investigates the interference exposure of the macrocell tier on the small cells in regards to the small cell's distance to the macrocell Base Station (BS), the small cell transmission power, the environment shadowing and macrocell load level. The results can serve as essential guidelines for operators when estimating the effective capacity of small cells in co-channel deployment scenarios.**

Keywords-component; Small Cell Networks, Co-Channel Deployment, Other-Cell Interference, Uplink, Capacity Estimation

I. Introduction

Owing to the ever-increasing data traffic demand in today's mobile networks, small cells are envisioned as an effective solution to improve the network's capacity through spatial reuse of wireless resources. In addition to the capacity, with up to 80 percent of the traffic being originated from the indoor [1] where the penetration losses of buildings are high, coverage is another concern of the operators which can be simultaneously addressed by small cells that are deployed in the home, enterprise or public areas. The small cells can operate either within the spectrum of the hosting macrocell network or on a dedicated frequency. While the former is more appealing to operators due to the improved spectral efficiency, the interference between the two tiers can potentially result in coverage inconsistencies (holes) and service outage. Considering these constrains, our earlier study [2] shows that the co-channel operation of small cell and macrocell is feasible without scarifying the coverage performance when small cells' public access is allowed.

This paper investigates the effect of uplink interference from the macrocell users to the small cells tier. Considering interference limited WCDMA systems, the capacity depends on the total interference from all the users in which the interference generated by users located in inter-cells (known as other-cell interference) is the key component [3]. While the other-cell interference is extensively studied in the literature for legacy macrocell networks, no study has addressed this issue in details for heterogeneous networks. The impact of macrocell interference to the small cell tier is particularly vital for operators to estimate the expected capacity of small cells in co-channel deployment scenarios. Additionally, in contrast to the study of interference from the neighbouring macrocells when the cells are of hexagonal shape and with similar traffic load, the estimation of interference from macrocell tier to a small cell BS is not trivial due to the variety of parameters impacting this quantity (e.g. distance of small cell BS to the macrocell BS, small cell BS transmit power, macrocell load etc).

Existing studies on the macrocell to macrocell interference include the work in [4] where the first and second moment of other-cell interference is evaluated under the assumption of uniform distribution of users over a cluster of hexagonal cells. The work in [5] extends the model of [4] and presents the upper bounds of the other-cell interference parameter in CDMA networks. However, through a simulation study, it is shown in [6] that the upper bound results presented in [5] could be much higher than the actual quantities which can lead to underestimation of the cells' capacity. The model in [4] is further extended in [7] by considering the distribution of users and BSs as Poisson processes. The work in [8] presents an analytic framework to evaluate the other-cell interference in the uplink of WCDMA cellular networks. To simplify the computation, the study suggests log-normal approximation of the other-cell interference distribution and then an iterative algorithm for solving fixed-point equations is used by the paper to derive the first and second moment of the other-cell interference.

Since uplink is known to have significant impact when evaluating the overall capacity of WCDMA systems [3] [6], this study address the interference effect of macrocell users on the small cells uplink performance. This is particularly relevant when considering this interference scenario to be the worst type when small cells are deployed at the edge of the hosting macrocell where they are most beneficial due to their extended coverage. The rest of this paper is organised as follows. The problem formulation is presented in Section II and the parameters of the model are described in Section III. Section IV presents the numerical results and discusses them and finally Section V concludes the paper.

II. Problem Formulation

In this paper, a standard 3GPP-compliant WCDMA network consisting of two tiers a macrocell tier and a small-cell tier is assumed. Both tiers serve the network users simultaneously over a shared frequency band.

Formally, the model assumes (i) a set U of active users, and ii) a cluster of macro/small cells. The serving cell of the user of interest, u, is denoted by $C(u)$. The Signal to Interference plus Noise Ratio (SINR) of the user u, before applying the spreading (processing) gain, at its serving cell $C(u)$ is formulated as

$$SINR_u = \frac{P^{RX}_{C(u),u}}{I_{C(u)} + noise} \tag{1}$$

Where $P^{RX}_{C(u),u}$ is the received power of the user u at its serving cell $C(u)$, $I_{C(u)}$ is the overall interference at the serving cell of the user u and *noise* is the additive signal noise. The interference $I_{C(u)}$ at the serving cell of the user u consists of two parts, namely $I^{own}_{C(u)}$ and $I^{others}_{C(u)}$. Defining the set $U(u)$ of users attached to the user- u's own serving cell $C(u)$ (so-called intra-cell users), the former term $I^{own}_{C(u)}$ represents the total interference from all intra-cell users at $U(u)$:

$$I^{own}_{C(u)} = \sum_{j \in U(u) \backslash u} \alpha_i P^{RX}_{C(u),j} \tag{2}$$

Where α_i represents the activity factor of user j. the latter term, $I^{others}_{C(u)}$ represents interference from all other users, i.e., from all users within the network except of the those that are attached to cell $C(u)$ (so-called inter-cell users):

$$I^{own}_{C(u)} = \sum_{j \in U \backslash U(u)} \alpha_i P^{RX}_{C(u),j} \tag{3}$$

The overall wideband noise rise can be defined as the ratio of total received wideband power to the noise power:

$$\Lambda = \frac{\sum_{j \in U} \alpha_i P^{RX}_{C(u),j} + noise}{noise} \tag{4}$$

The uplink Power Control (PC) is an essential functionality to overcome the near-far problem in WCDMA systems where a strong interfering signal captures a receiver making it impossible for the receiver to detect a weaker signal. Practically, this is realised by enabling the users to adjust their output power in accordance with the Transmit Power Control (TPC) commands received in the downlink from their associated BS (or multiple BSs during the soft handover). Therefore, each user u periodically updates its transmit power P^{TX}_u to maintain a desired target value $SINR_u$ at the serving cell $C(u)$ in time t. Denoting the channel gain between the user u and the base station $C(u)$ as $G_{C(u),u}$, it is formally assumed that the transmit power P^{TX}_u of user u is updated in time $t+1$ on the basis of the interference $I_{C(u)}(t)$ at the base station i in time t to

$$P^{TX}_u(t+1) = \frac{SINR_u I_{C(u)}(t)}{G_{C(u),u}} \tag{5}$$

The high frequency (1500Hz) of power update procedure enables users to track fast variations of the wireless channel. The stability of the PC is defined as

- The existence of unique positive TX powers $P^{*TX} = -(A-E)^{-1}B$ that satisfy users' SINR targets
- The exponential convergence of PC schemes (5) to P^{*TX} under any network scenario

Where

• P^{*TX} is a power vector whose u-th component is P_u^{*TX}

• B is a vector whose u-th component is $\frac{SINR_u noise}{G_{C(u)}}$

• A is a matrix whose element in u-th row and v-th column is $\frac{SINR_u G_{C(u),u}}{G_{C(u)}}$ if $u \neq v$ *and 0* otherwise.

• E is the identity matrix of the size of A.

Throughout the study, the capacity C of the entire macro cell/small-cell network is defined as [9]

$$C = \max_{\forall i} |\lambda_i| \geq 0 \tag{6}$$

where λ_i is the i^{th} eigenvalue of the network information matrix A [10]. The motivation consists in the fact that the inequality $\forall i, \max|\lambda_i| \leq 1$ is a both necessary and sufficient condition for the stability of the network-wide PC [11]. Accordingly, the subsequent analysis considers only realistic topologies and traffic conditions characterized by C ≤ 1 in which networks channel gains and target SINR values for all users always admit a matrix A such that $\max|\lambda_i| < 1$ .In practical terms, the eigenvalue-oriented definition of network capacity results in no loss of applicability of the presented results as our previous contribution [12] defines a distributed scheme for real-time medium access that is able to fully exploit the capacity (6). From an analytical point of view, however, the definition allows to perform the aforementioned study only by numerical means because closed-form formulas for eigenvalue computation do not exist if the network has more than four links [13]. The spectral radius $\forall i, \max|\lambda_i|$ of A can be under certain conditions expressed implicitly to allow for a non-numerical analysis. Nevertheless, such conditions are too restrictive and/or unsuitable for our purposes. For example, previous studies on macro-cell networks [14] define the network capacity as

$$C' = 1 - \frac{1}{\Lambda} \tag{7}$$

The motivation is the fact that the communication channel is interference-limited and $P_u^{*TX} \approx 1/(1-|\lambda_1|)$ [15].Under suitable assumptions (channel gains defined by exponential path-loss, symmetric topologies with hexagonal cells, user distribution given by Poisson point process, etc.), the simple dependence of C′ on powers PTX allows to characterize C′ by using closed-form expressions. Nevertheless, owing to the random nature of small cell deployments, it is difficult to capture the assumed two-tier network by such models accurately. Moreover, the definition of C' is more conservative (i.e., suboptimum) than the definition of C on the basis of PC stability as $C' < C$ [9]. Most previous studies model the number of users in each cell as an independent $M/G/\infty$ queue, which implies there is no call admission control considered [8]. Further, the limitation of users' transmit power on the uplink is another critical considerations that significantly impact the complexity and tractability of analytical interference (hence capacity) investigations. This is especially important when considering large number of indoor users where the radio signal loss due to wall penetrations could be as high as 25 dB.

III. SYSTEM MODEL

The macrocell tier considered in this study consists of 19 hexagonal shaped cells where a small cell BS is deployed within the central cell. The macrocells' Inter Site Distance (ISD) is set to 750m. While the distance between the small cell BS and the hosting macrocell BS as well as the macrocells' fractional load are varied during the simulations, the default values of 300m and 0.75 are used respectively. Because, the small cell users normally transmit at much lower power, the impact of small cell users on the uplink of the macrocell tier is neglected when the macrocell fractional load is evaluated. Additionally, a target SINR value of 7dB is considered both for the macrocell and small cell users. The macrocells' transmit power is set to 20W and for the small cell BS, three values of 1W, 250mW and 100mW are evaluated. The simulations are repeated for 1000 times to average the impact of users' location. Table I summarises the parameters of the propagation model used in this study.

Table I: Summery of simulation parameters

Path-loss	Path-loss is modelled as $11.81+38.63\log_{10}(d)$ for macrocell users and $29.94+36.70\log_{10}(d)$ for small cell users where d is the distance from the base station in meters.
Shadow fading	Shadow fading is modelled as spatially correlated random process with log-normal distribution (6 dB standard deviation for the macrocell signal, 4 dB standard deviation for the femtocell signal, spatial correlation $r(x) = e^{x/20}$ for distance x
Receiver noise power	The receiver noise power is modelled as $10\log_{10}(kT\ NF\ W)$ where the effective noise bandwidth is given as $W = 3.84 \times 10^6$ Hz, and $kT = 1.3804 \times 10^{-23} \times 290$ W/Hz. The noise figure at the UE is $NF_{[dB]} = 7$ dB.
Macrocell antenna gain	The macrocell antenna gain is calculated as $G(\theta)dB = G_{max} - \min\left[12\left(\frac{\theta}{\beta}\right)^2, G_s\right], \quad -\pi \le \theta \le \pi$ with $\beta = 70\pi/180$ angle where gain pattern is 3dB down from peak $G_s = 20$dB sidelobe gain level in dB $G_{max} = 16$dB maximum gain level in dB

The radio propagation model consists of a log-distance path loss model with the fixed and exponent coefficients taken from [15]. The amplitude change caused by shadowing is often modelled using a log-normal distribution with a standard deviation according to the log-distance model. The shadow fading maps were generated based on the method in [16] with the standard deviation parameters taken from [15]. Since this later parameter has a significant impact on the total interference [5] [6], the parameter value is explicitly varied during the experiments.

IV. NUMERICAL RESULTS

Considering the open access architecture for the small cells [2], the coverage radius of small cell BS is a critical parameter impacting the level of uplink interference from the macrocell users to the small cell BS (this is discussed later in details). Figure 1 illustrates the average coverage radius of a small cell BS in relation to its distance from the hosting macrocell BS. As the Figure shows, owing to the attenuation of the macrocell signal with distance, the small cell coverage radius increases almost linearly with the increase of distance between the small cell and macrocell BSs. Additionally, higher transmission power of small cell BS expectedly results in the expanded coverage.

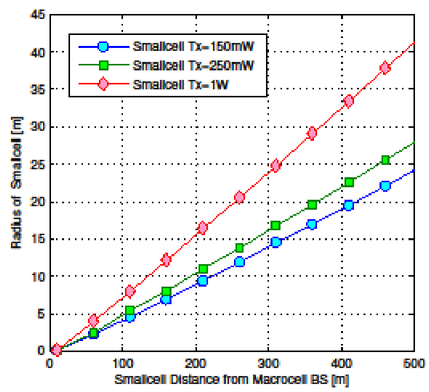

Figure 1: Small cell coverage vs. distance to the macrocell BS

Since this study concentrates on the uplink interference from the macrocell tier, the reported noise rise figures ignore the intra-cell component in order to provide a better understanding of the other-cell interference impact. Figure 2.a shows the noise rise at the small cell BS due to the interference from the macrocell users when the macrocell tier fractional load is set to 0.75 (all cells). Additionally, the ratio of the inter-cell to the intra-cell interference is commonly expressed as the other-cell interference factor. For legacy macrocell networks, field measurements suggest the value of 0.55 to 0.65 for this quantity [3]. However, the situation is entirely different when it comes to the small cells. This is firstly due to the positioning of the small cells that are co-located within the coverage area of the macrocell tier making them being exposed to the interference from macrocells users in their vicinity. Secondly, owing to their reduced coverage, small cells are normally less utilised compared to the macrocells which again implies a higher other-cell interference factor. Figure 2-b shows the other-cell interference factor for the small cell when the cell consists of 2 users with the target SINR values of 7dB.

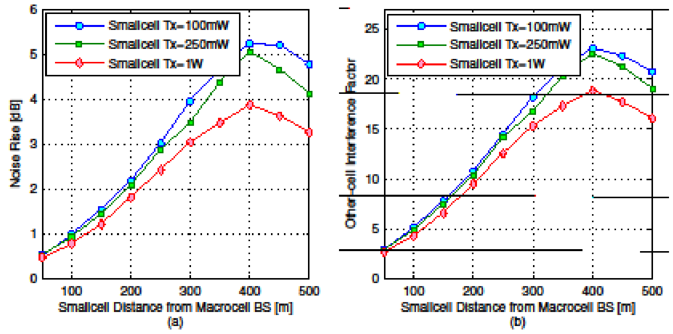

Figure 2: a) Noise rise due to other cell interference versus small cell distance to the macrocell BS b) other-cell interference ratio for small cell consisting of two users

Considering the results of Figure 2, there are two effects that impact other-cell interference when the small cell BS is moved away from the hosting macrocell BS. With the increase of distance between the small cell BS and macrocell BS, from one hand, the macrocell users need to transmit on higher power to reach their BS which implies increased other-cell interference. On the other hand, since the macrocell downlink signal is simultaneously attenuated, the small cell coverage expands (see Figure 1). This coverage expansion implies an increased minimum distance between the small cell BS and the interfering macrocell users in the vicinity of the small cell which effectively results in reduced other-cell interference. Considering the trend of results in Figure 2, it is apparent that unless the small cell BS is deployed at the macrocell edge, the effect of macrocell users' transmission power is dominant. Therefore, the total interference is increased with increasing the small cell distance to the hosting macrocell BS. This continues until a certain point (400m) from where the effect of small cell coverage radius becomes the dominant parameter and further increase of the distance results in lower other-cell interference. Additionally, higher small cell transmit power results in an increased cell coverage which subsequently lowers the other-cell interference.

However, not only the distance but also the angular offset of the small cell BS from the centre of the hosting macrocell's antenna beam (denoted as φ) impacts the other-cell interference. For example, for a given distance, the macrocell users that are facing the main beam of the macrocell antenna benefit from higher reception gain and subsequently need to transmit at lower power. Similar to the effect of distance, the counter effect of this angular offset is the attenuation of the macrocell signal in the downlink direction and the expansion of the small cell's coverage as the result.

Figure 3-a confirms this understanding by illustrating the noise rise due to the macrocell users interference at the small cell BS when the φ angle is varied and the distance of the hosting macrocell BS and the small cell BS is set to 250m. For lower small cells transmit power, the effect of macrocell higher transmit power from the macrocell users' transmission power is always dominant and therefore the interference rises with the increase of the offset angle φ.

The effect of small cell coverage expansion becomes pronounced when considering higher transmit power for the small cell and when the offset angle is relatively high (50° and above). In this case, the total interference starts to flatten/decrease with the increase of φ. Additionally, with the higher offset angles the small cell BS would be closer to the neighbouring macrocell (with φ=60° referring to the edge of the hosting macrocell). Figure 3-b, captures the ratio of the interference from the hosting macrocell's users to the total combined interference from users of all cells. As expected, the ratio starts to decrease with the increase of distance from the hosting macrocell BS and with the rise of φ angle.

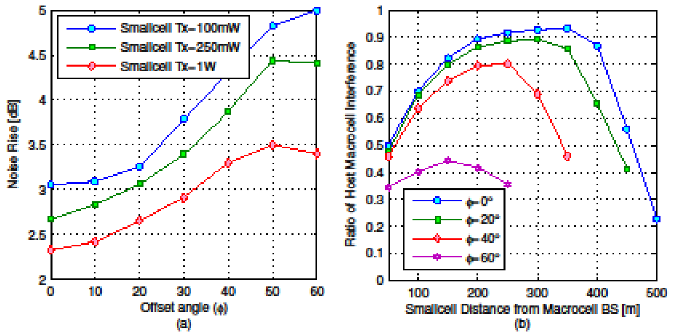

Figure 3: a) Noise rise due to other cell interference versus φ (in degrees) b) ratio of hosting macrocell's interference to the total interference imposed to the small cell BS (Small Cell Tx=100mW)

Figure 4 shows the impact of standard deviation of the shadowing both for the macrocell (σ_m) and small cell (σ_s) tiers. Generally, higher shadowing for macrocell results in expansion of distribution of users' transmit power and subsequently results in higher other-cell interference. Additionally, similar effect is observed by increasing the standard deviation parameter of shadowing, for small cells.

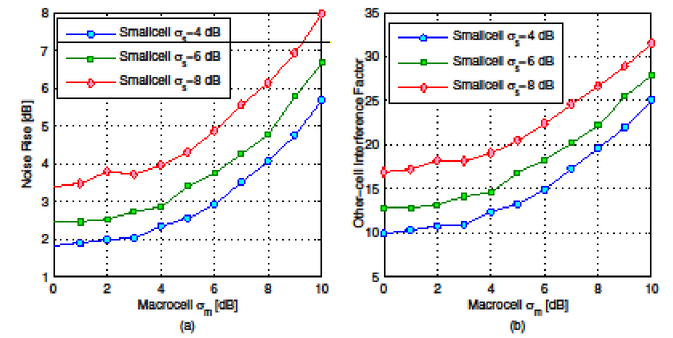

Figure 4: a) Noise rise due to other cell interference versus σ_m for different values of σ_s b) other-cell interference ratio for small cell with two users

Figure 5-a and 5-b show the effect of macrocells' fractional load (calculated as the ratio of users to the pole capacity of the cell) on the interference imposed to the small cell. As expected, the interference increases significantly with the macrocells' load. Further, as the Figures show the increase of the interference becomes more significant as the macrocell reach to its capacity. For example, the noise rise due to macrocell interference is increased by nearly 3dB when the fractional load is changed from 0.9 to 0.95. This suggests that the offloading of heavily utilised macrocells (e.g. in urban and dense-urban deployments) through small cells could be very beneficial not only for the macrocell users but for the small cell users as well.

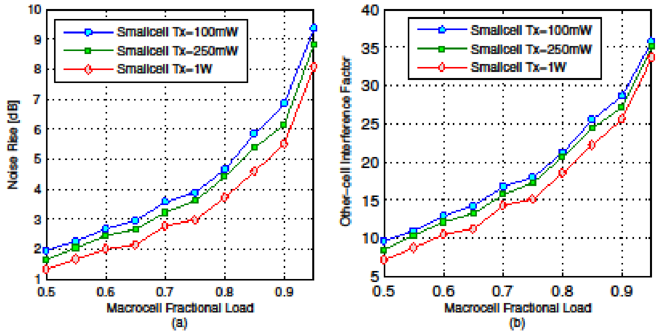

Figure 5: a) Noise rise due to other cell interference versus macrocell tier fractional load BS b) other-cell interference ratio for small cell consisting of two users

The results presented above are for outdoor deployment of small cells. On the other hand, when considering the indoor deployments, two scenarios exist. The first scenario refers to the case where the indoor environment is fully covered by the small cell (or a cluster of small cells). In this case the total other-cell interference is reduced due to the isolation provided by walls between the macrocell and the small cell tier. However, in the second case where the indoor coverage of the small cell(s) is partial, the total interference could be worse since the indoor macro users located in vicinity of the small cell BS need to transmit at very high power to overcome the wall's losses and to reach to their far BS. This implies that the coverage optimisation is very critical when indoor deployment of small cells is considered.

V. Conclusion

Interference is considered as the main concern for the co-channel deployment of small cell and macrocell networks. The problem formulation is presented and it is shown that the mutual interference between the macrocell and small cell tier can not be analytically traced. The work in this study investigates the impact of interference from macrocell users imposed to the small cell BS on the uplink direction. Interestingly, it is shown that this interference is not maximised at the macrocell edge as one might expect. This is due to the fact that the small cell coverage would also simultaneously expand when moving away from the macrocell BS, mitigating the effect of higher transmit power from macrocell users. The same argument holds true when considering the effect of angular offset from the macrocell's main antenna beam. Further, the effect of shadowing is shown to be important when evaluating the total interference. This is observation is in line with the findings of previous studies which consider other-cell interference in homogeneous networks consisting of macrocells only. Finally the effect of macrocells' fractional load on the overall interference is quantified. This study is particularly important for the operators to assist them in evaluation of the effective capacity expected from small cells when deployed on the co-channel frequency as the existing macrocell networks.

VI. References

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