On Uplink Intercell Interference in a Cellular System

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Abstract—**A new semi-analytical method to analyze intercell interference in a cellular system is introduced. A sound comprehension of the properties of intercell interference is the key to a meaningful assessment of communication systems without exhaustive simulation campaigns. We consider the basic access schemes TDMA, WCDMA and random OFDMA for uplink transmission. We will also give hints, how the methods can be extended to capture other access schemes, and/or additional features.**

The focus of this work is more on the introduction of the new methodology. In principle, we describe the intercell interference as a random variable which is composed of many other random variables. The distributions, and in particular the mutual dependencies of those have to be carefully studied.

Applications and extensions of the ideas will be addressed in future work, only first examples are given here.

I. Introduction

Intercell Interference is the key difference between a cellular communication system and non-cellular applications like WLAN [1]. Subscribers of a cellular system such as GSM or UMTS expect ubiquitous coverage and do not accept uncovered areas. On the other hand, in order to offer the services for economical conditions, the operators have to reuse their expensive spectrum in the cells [1].

In order to allow for high peak data rates, there is the strong desire to use the entire spectrum in every cell. This is typically referred to as *frequency reuse*=1, in contrast to a *frequency reuse*>1, where adjacent cells use different parts of the spectrum. With reuse=1 (and the need of ubiquity), the communication system has to cope with overlapping cells and thereby with strong interference from neighboring cells which is called intercell interference. With a reuse of e.g. 3, intercell interference is less severe though still present, however only 1/3 of the entire spectrum is available for each cell.

Due to the significance of the intercell interference problems, any conclusions drawn from single-cell investigations might be extremely misleading. However, multi-cell investigations are exhaustive. In many cases, vastly simplified intercell models are applied, but it is always hard to show that the crucial effects are still captured.

In WCDMA which has dominated the communications community during the last decade, the assumption of AWGN structure for the intercell interference shows a rather good match with reality [2], [3]. In former times of TDMA systems such as GSM, multi-cell investigations have been carried out by explicitly simulating co-channel (i.e. non-Gaussian) interferers. A Gaussian (and the "white") assumption would have been by far too crude.

Due to the superior intracell behavior, future systems will most likely be based on OFDM, e.g. WiMAX, Flash-OFDM, Evolved UTRA, 4G/WINNER. The origin of the OFDM idea is located in broadcast scenarios, where intercell interference is not an issue. Whether or not an AWGN assumption is reasonable, does not appear directly obvious.

For the sake of early assessment of emerging new technologies, it would be extremely helpful to have intercell models which allow for simpler evaluation compared with demanding multi-cell system level simulations. In this work we try to make a first step towards this goal by deriving a semi-analytical model for the uplink intercell interference.

A. Motivation: Intercell Interference is unpredictable

In future systems, each cell tries to adapt its transmission strategy to the current situation as quick as possible. In particular, "current situation" not only accounts for the varying channel (bit/power loading, link-adaptive scheduling), but also, although not less important, for the extremely bursty traffic behavior. Note that the time scale of assigning resources to the users is typically in the range of milliseconds. The result is that the interference produced by one cell for the others is extremely varying.

One could think about "measure and react", i.e. the entire link adaptation measures the intercell interference and reacts accordingly. However, in case of a collision of two resources (i.e. "worst case" interferer), both involved allocators would avoid this resource in the next time instance, but the probability to collide in another resource would be exactly the same as before. In addition, both resource allocators permanently update their decisions anyway, so in many cases collisions will only occur for a single time instance. Hence, "measure and react" is a viable option only in (close to) circuit switched systems, where any adaptation of resource allocation occurs on a very slow time scale. This leads to the principle conclusion that *intercell interference is unpredictable*.

The only exception would be a central unit, which controls all base stations, has full knowledge of all links (buffers, channel states etc), and has the capability to quickly influence the transmission strategy on the physical layer ("genie scheduler"). However, this is not possible with current system architectures, since backhauling of the base stations is very expensive. In addition, the signalling would be by far too slow and the scheduler complexity too high. However, it is an interesting research topic, and it has to be checked to which extent such concepts could be applied to 4G systems.

As for now, we have to live with the aforementioned statement that intercell interference is unpredictable, making the intercell

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interference a random variable. This suggests that a careful analysis of the statistical properties will give valuable insights about the cellular performance of a specific access scheme. Later on, we will see that the expressiveness of moments is not sufficient, therefore we will focus on deriving probability density functions.

B. Basic Solutions

In principle, there are two ways of combating intercell interference:

- **Interference Avoidance:** The system tries to avoid collisions. This could be done in a static way, e.g. neighboring cells use different resources (reuse > 1, e.g. in GSM). A dynamic way, where intelligent resource allocation takes care of collisions, would be more efficient — however, we have already discussed the inherent problems of a "genie scheduler" above.
- **Interference Averaging:** The system tries to statistically average the interference such that the level remains as constant as possible (e.g. WCDMA). Then the transmission parameters (e.g. code rate, modulation etc) can stably be designed for a well defined operational area. Note that many interferers are desirable in order to benefit from the law of large numbers (always "good" and "bad" interferers are present). Of course, each interferer should contribute only with a part of its power to the intercell interference (e.g. spreading factor).

II. Basics of Uplink Intercell Interference

A. Principle Description

The principle assumption is, that the base station BS of interest detects a code word of a particular user. For convenience, we do not use subscripts for the (BS) and the mobile station (MS) of interest. The amount of intercell interference[1] in this code word is given as

$$I = \sum_{u=1}^{\infty} P_u \cdot L_u \cdot B_u \cdot o_u \tag{1}$$

where P_u is the transmit power of user u, L_u is the attenuation between user u and the BS of interest and B_u is the gain value of the antenna pattern of the BS of interest towards user u. We denote o_u the *suppression factor*, which accounts for the fraction of the transmit power P_u which will be visible as intercell interference for the code word detection of the user of interest [4], [5]. The sum runs over all intercell users u in the system, i.e. intracell users are NOT considered here.

The principle idea is to model I as a random variable for which we want to gain as much insights as possible.

B. Cellular Grid

Later on, we will see that exactly modelling some important properties of the random variables requires grouping all the interfering users into cells. Although not directly obvious from equation (1), this is also the typical way to illustrate a cellular system.

We will assume hexagonal cells of equal size [1], [6]. Two different topologies are considered as depicted in figure 1. In the *omni* case, the BS is located in the center of the cell and the antenna elements have an omnidirectional pattern (i.e. $B_u = 1$). In the *sectorized* case, a single BS serves 3 different cells (sometimes referred to as *sectors*) from a common location. The latter structure is a typical consequence of commercially available antenna elements with a 3dB beamwidth in the range of $\approx 70^o$ (only half of the distance has to be covered at the sector edge $\pm 60^o$). The concept of frequency reuse is illustrated as well in figure 1, but will be explained later on.

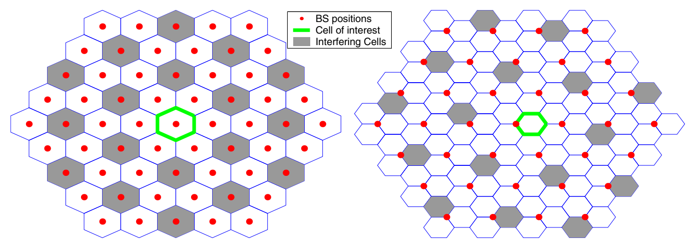

Fig. 1. Omni (left) and Sectorized (right) Cell Topology and Examples for Frequency Reuse 3 (left) and 7 (right)

The BS locations are denoted $\vec{p}_{B,c}$ (c is the cell index), and the BS of interest is located in the origin $\vec{p}_{B,0} = (0, 0)$. For simplification, we introduce the position of the cell center $\vec{p}_{C,c}$ which is different from the BS position in the sectorized topology. The user positions with respect to the BS of interest are denoted by $\vec{p}_u$. Note that the BS and cell positions are deterministic, meanwhile the user positions are random variables.

Each user u is associated with the cell in which it is located, and with the BS serving this cell. Figure 2 illustrates the aforementioned definitions.

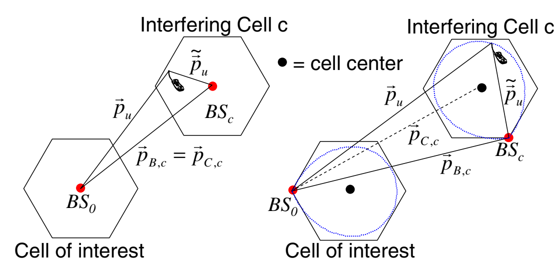

Fig. 2. Geometric Relations for omni (left) and sectorized (right) with antenna pattern (blue)

III. Attenuation, Sector Pattern and Tx Power

The parameters in this section are independent from the multiple access schemes, unless stated otherwise.

A. Attenuation

The attenuation is composed out of three components:

1. The **Pathloss** is a deterministic function of the random distance between user u and BS of interest $|\vec{p}_u|$. It is typically

[1] For convenience, we do not distinguish between energy and power, this would complicate matters without adding more information.

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described by an exponential pathloss law:

$$10 \cdot \log_{10}(L_u^{pathloss}) = -A - B \cdot \log_{10}(|\vec{p}_u|/R_0) \quad (2)$$

where R_0 is a reference distance.

2. The effect of **Shadowing** is typically modelled as a random variable with a log-normal distribution with zero mean and variance σ^2_{shadow}:

$$10 \cdot \log_{10}(L_u^{shadow}) = \mathcal{N}(0, \sigma^2_{shadow}) \quad (3)$$

3. **Small Scale Fading** is also assumed to be a random variable. With the typical assumption of L-path Rayleigh fading, the distribution becomes a chi-square χ^2_{norm} distribution with $2L$ degrees of freedom where the subscript $_{norm}$ denotes the normalization such that the mean is always 1:

$$L_u^{smallscale} = \chi^2_{norm}(2 \cdot L) \quad (4)$$

Finally, the overall attenuation becomes

$$L_u = L_u^{pathloss} \cdot L_u^{shadow} \cdot L_u^{smallscale}. \quad (5)$$

B. Sector Pattern

Similar to the pathloss, the gain by the antenna pattern is a deterministic function of the random direction of the angle $\arg(\vec{p}_u)$ of user u.

Note that the antenna pattern B_u must be chosen such that it matches the assumed cellular grid. As already mentioned in section II-B, a pattern with $\approx 70^o$ will roughly generate a hexagonal structure as in figure 1 (right). In the omni case (left), we obviously have $B_u = 1$, independent of the directions $\arg(\vec{p}_u)$.

It is also important to mention, that there is a non-zero backward attenuation. Neglecting this effect would have significant impact on the results.

C. Transmit Power

The transmit power P_u depends on the situation in the "own" cell, i.e. the cell served by the BS with which user u is connected.

However, in a first step the considerations of the previous section can be adopted by replacing the variables

$$L_u, L_u^{pathloss}, L_u^{shadow}, L_u^{smallscale}, B_u, \vec{p}_u$$

with their "own cell" equivalents

$$\tilde{L}_u, \tilde{L}_u^{pathloss}, \tilde{L}_u^{shadow}, \tilde{L}_u^{smallscale}, \tilde{B}_u, \tilde{\vec{p}}_u.$$

The distribution of the random variables will be the same as previously described. However, the distribution of small scale fading $\tilde{L}_u^{smallscale}$ might be influenced by scheduler decisions of the serving cell. In this case, it would no longer be a χ^2 distribution. Depending on the scheduler strategy, it should be a more advantageous one, which could even have an average larger than one.

We make the assumption, that there is a power control which is able to follow and thereby compensates the small scale fading. Note, that in the uplink there will always be some kind of power control.

In this case, the transmit power would be such that a particular receive power level $\tilde{P}_u^{Rx}$ is achieved, i.e.

$$P_u \cdot \tilde{L}_u \cdot \tilde{B}_u = \tilde{P}_u^{Rx} \quad (6)$$

where the tilde again denotes the "own cell" character of the receive power. The different $\tilde{P}_u^{Rx}$'s typically accounts for some fairness strategy by the operator. Basically, two strategies are reasonable:

1. Same service/rate for all users, also at cell edge (total fairness) [7], i.e.

$$\tilde{P}_u^{Rx} = \tilde{P}_0^{Rx} \quad (7)$$

2. Degrading service/rate at cell edge [8], i.e.

$$\tilde{P}_u^{Rx} = f(\tilde{\vec{p}}_u) = f(\tilde{L}_u^{pathloss} \cdot \tilde{B}_u) \quad (8)$$

In reality, there will be external influences such as "gold users" which also influences the power strategy. However, in order to keep things simple here, we focus on option 1 with same receive power level for all users.

In any case, $\tilde{P}_u^{Rx}$ should be chosen such that it can be achieved by user u emitting its maximum power $P_{u,max}$ from the cell edge (considering some fade margin) [9].

D. Correlations

We could have easily given analytic solutions for the PDF's of the random variables transmission power P_u, attenuation L_u and antenna gain B_u. However, correlations require a joint description of those random variables. It is obvious from figure 2 that the positions $\vec{p}_u$ and $\tilde{\vec{p}}_u$ are mutually dependent. As a consequence, with the arguing of the previous sections, there will also be correlations and dependencies between P_u, L_u and B_u, in particular for users which are close to the cell of interest. As those users are the most critical ones, neglecting these correlations would be dangerous.

On the other hand, analytical description of these correlations, as well as accordingly generating correlated random variables would be a highly challenging task. Therefore, we will not directly generate the random variables P_u, L_u and B_u, but we will make the detour over the user positions and the fading variables. P_u, L_u and B_u will be deterministic functions of those according to equations (2)-(8).

IV. Suppression Factor

So far, we have not observed any dependency on the access scheme (with the exception of the small scale fading in the own cell $\tilde{L}_u^{smallscale}$). Indeed, the fact that power has to be invested to compensate for physical and geometrical effects is given by nature and not by a particular access scheme.

However, when discussing the suppression factor o_u, the access scheme plays the crucial role. Recall that o_u expresses the fraction of the transmit power that acts as interference for the code word detection of the user of interest.

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A. WCDMA

The simplest case is WCDMA, where every user in the system produces interference to the code word. Considering the pseudo-orthogonal cell-specific scrambling code, despreading leaves exactly $\frac{1}{SF}$ of the power of any user in the code word. Note that we are looking only at inter-cell users, where no orthogonality can be maintained by the spreading codes. Hence, o_u is deterministic and simply becomes [10]

$$o_u = \frac{1}{SF}. \tag{9}$$

B. TDMA

For simplification, we will consider a pure TDMA system without frequency hopping during a codeword. The code word covers a single timeslot, and the system is driven with the load factor η, i.e. the fraction η of the available time slots are occupied ($0 \leq \eta \leq 1$). Furthermore the BS's are synchronized. Later on, we will be able to assess, how these assumptions affect the results.

There is the probability η for exactly one user in each cell causing interference to the code word of interest. However, the power of this user is not suppressed at all. All the other users are not visible for the code word of interest. Hence, o_u is random for a single user in each cell, and the distribution writes as

$$f_{o_u}(o_u) = \begin{cases} \eta & for \quad o_u = 1 \\ 1-\eta & for \quad o_u = 0 \\ 0 & for \quad o_u \neq 0, 1 \end{cases}. \tag{10}$$

The other users have $o_u = 0$ (deterministic) and thus need not to be modelled.

Note that these considerations are valid not only for TDMA, but also for other systems without any ability of interference averaging, e.g. localized/distributed FDMA [11].

C. Random OFDMA

In addition, we look at an OFDMA system, where

- N users share
- N_T tones, such that each user u is allocated
- $n_u = \frac{N_T}{N}$ tones which are randomly distributed across the N_T tones. Within a codeword the random distribution is independently repeated
- N_H times (N_H hops, *tone hopping*). Each hop covers
- N_S OFDM symbols, i.e. a user codeword covers $N_H \cdot N_S$ OFDM symbols, or $N_H \cdot N_S \cdot n_u$ information symbols, respectively.

Such an access scheme is applied for instance in IEEE802.16 or in Flash-OFDM. Similar to the TDMA case, we assume BS synchronization. For simplification, all users have the same number of tones n_u. Deriving the suppression factor for such an OFDMA system becomes a combinatorial problem of tone collisions. Obviously, o_u is random again. Considering a single OFDM symbol, the probability of colliding with user u in x tones is

$$Prob(x) = \frac{\binom{n_u}{x} \cdot \binom{N_T - n_u}{n_u - x}}{\binom{N_T}{n_u}}. \tag{11}$$

Considering the aforementioned independent tone hopping, the number of tone collisions y in the entire code word is

$$y = \sum_{i=1}^{N_H} N_S \cdot x_i = N_S \cdot \sum_{i=1}^{N_H} x_i. \tag{12}$$

Finally, the suppression factor o_u becomes

$$o_u = \frac{y}{N_H \cdot N_S \cdot n_u}. \tag{13}$$

A closed form PDF could be easily given by combining equations (11)-(13). Basically it would be a convolution of the expression (11). However, we omit the closed form expression here since it would be very bulky and would not help us here.

So far, we have looked at the suppression factor of a particular user with respect to the user of interest. However, there are multiple users in each cell which, in a first step, have a joint distribution with the same marginal distributions. In other words there might be dependencies among the random variables o_u's.

Indeed, there is a constraint on the o_u's in a particular cell. Let us assume a fully loaded cell ($\eta = 1$), i.e. all tones are occupied. In this case, the number of total tone collisions y (with users in one cell) is exactly the number of symbols in the code word of interest $N_H \cdot N_S \cdot n_u$, or

$$\sum_{u \in \mathcal{C}_c} o_u = 1 \tag{14}$$

respectively. $\mathcal{C}_c$ is the set of user indices which are connected to cell c. Note that in the case of a less loaded system $\eta < 1$, the sum would be a random variable as well, however still limited by 1.

Such a constraint is very difficult to incorporate into the calculations above. A brute force method to fulfill the constraint would be the simple normalization

$$o_u^{(temp)} = \frac{o_u}{\sum_{u \in \mathcal{C}_c} o_u}. \tag{15}$$

However, this changes the marginal distribution. In particular, mean and variance have changed. We can restore mean and variance by the *re-normalization*

$$\hat{o}_u = \sqrt{var(o_u)} \cdot \frac{\left(o_u^{(temp)} - \mathbf{E}\left\{o_u^{(temp)}\right\}\right)}{\sqrt{var(o_u^{(temp)})}} + \mathbf{E}\left\{o_u\right\} \tag{16}$$

where the $\hat{o}_u$'s are simply shown to still observe the condition (15). Figure 3 shows the CDF's of the true, the normalized and the re-normalized suppression factors o_u, $o_u^{(temp)}$ and $\hat{o}_u$, respectively. Without re-normalization, there is a significant deviation, in particular for a low number of users. After re-normalization, we are very close to the true case, even though the discrete nature of o_u obviously got lost. This is not surprising, since we can observe that the shape of the marginal o_u distribution is similar to a Gaussian distribution. Therefore, restoring mean and variance also restores most of the statistical properties.

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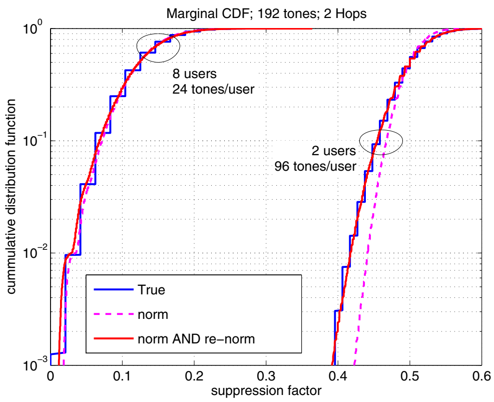

Parameters	
N_T	192
N	2(8)
n_u	24(96)
n_0	24(96)
N_H	2
N_S	n.r.$^{*)}$

$^{*)}$not relevant

Fig. 3. Interference Suppression Factor for Random OFDMA

As a conclusion, we have found a simple way to model a good approximation $\hat{o}_u$ of the complicated random suppression factors o_u. Note that very similar approaches could be pursued to model other interference averaging access schemes such as frequency hopping (e.g. for GSM), TDMA/FDMA with unsynchronized cells, etc.

D. *Further Constraints and Frequency Reuse*

During our investigations, we have already assumed at various places that the users are grouped into cells. In particular:

- The suppression factors for TDMA and random OFDMA have some intracell constraints.
- The number of users in a particular area is restricted, i.e. extreme user concentrations can not occur.
- Considering frequency reuse, not every cell contains interferers.

In order to come up with such constraints, we split the user sum in (1) into cells and users per cell:

$$I = \sum_{c \in \mathcal{Z}} \sum_{u \in \mathcal{C}_c} P_{c,u} \cdot L_{c,u} \cdot B_{c,u} \cdot o_{c,u} \tag{17}$$

where $\mathcal{Z}$ is the set of cells that can produce intercell interference (same carrier frequency). This set is given by the reuse strategy [1]. Figure 1 shows the reuse strategies for a reuse of 3 (left) and 7 (right). $\mathcal{Z}$ contains the indices of the cells / sectors marked in gray, for which the coordinates of the sector center $\vec{p}_{C,c}$ and of the serving BS $\vec{p}_{B,c}$ are needed (cf. figure 2).

Note that frequency reuse is to be understood sectorwise, i.e. it generates the same pattern, irrespective of the omni and sectorized topology 2.

V. Evaluation Method

In principle, it would have been possible to give closed form solutions for the PDF's of the described random variables. However, in order to derive a PDF for the intercell interference I in a closed form, it would be necessary to analytically express the PDF of a product of 3 random variables, and afterwards the sum of many "product random variables". This would be quite impractical.

Therefore, we pursue a semi-analytical approach. We generate samples of the random variables as described in the previous sections, and then numerically evaluate a histogram of I, which should converge towards the PDF of I. This could be considered as a solution by *Monte-Carlo Integration* .

For this approach, the PDF's and correlations in closed forms would not have helped, and therefore we dropped the complicated mathematics to do so. Note that many analytical pre-evaluations are used, and hence we are still significantly faster compared with a system level simulation.

We will now summarize the whole procedure to derive the PDF approximation of the Uplink intercell interference.

1. Initialization: generate BS and center positions $\vec{p}_{B,c}, \vec{p}_{C,c}$ for all interfering cells $c \in \mathcal{Z}$, considering reuse strategy. Determine target received power $\tilde{P}_{Rx}$
2. Draw user positions from a uniform distribution over the area of each cell.
3. For convenience, approximate the cell area as a circle around the cell center $\vec{p}_{C,c}$. Since we have assumed that the users are located uniformly over the cell, then the distance r from the center of the cell can be chosen from a linear distribution, and the angle θ from a uniform distribution.
4. Derive $\vec{p}_u$ and $\tilde{\vec{p}}_u$ according to figure 2.
5. Draw shadowing fading and small scale fading to both own BS c and BS 0 of interest.
6. Calculate transmit power P_u of each user according to equation (6).
7. Draw suppression factors o_u.
8. Calculate intercell interference sample I
9. Repeat procedure until a stable histogram of I can be set up.

Finally, the histogram will converge against the PDF of I.

VI. Example

We will now give an example for the three access schemes. For a fair comparison, we will assume 8 and 2 users for WCDMA (SF=8,2) and for Random OFDMA. For the TDMA case the number of users is not relevant, as long as the system is fully loaded (exactly one interferer). The rest of the parameters used in the example are shown in table I.

Cell Topology	sectorized
Pathloss law	$128.1dB + 37.6 \cdot \log_{10}(r/1km)$
Shadowing	$\sigma = 6dB$
Small Scale Fading	1-path Rayleigh
max. Tx Power	24dBm
Cell Radius	1km
WCDMA	$SF = 8, 2$ (Reuse 1)
R-OFDMA	cf. 3 (Reuse 1)
TDMA	$\eta = 1$ (Reuse 1,3)

TABLE I
Evaluation Parameters

The results are depicted in figure 4. It is obvious that WCDMA has the tightest PDF, since it performs the most efficient interference averaging. Random OFDMA is slightly worse. TDMA has no interference averaging at all, resulting

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in the broadest PDF. Furthermore, we observe a tail at the right edge, i.e. there is always a non-zero probability for having a very high I value. This does not change with introducing reuse 3, although at a much lower level. This tail is the reason why a reuse 1 deployment is highly critical for a pure TDMA system (without additional means such as frequency hopping or interference cancellation). Note that all distributions — except TDMA with reuse 3 — have exactly the same average (in the linear domain).

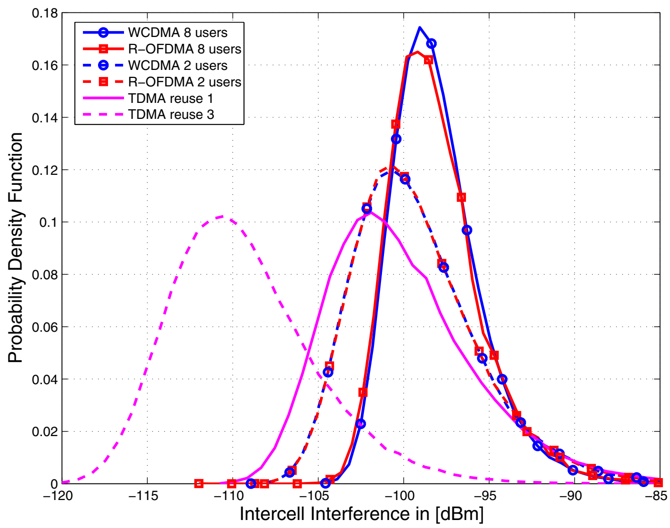

Fig. 4. Probability Density Functions of Intercell Interference

VII. Conclusion and Outlook

We have presented a method to evaluate and assess intercell interference for different access schemes in a semi-analytical way. The focus in this work was more on the methodology itself rather than on the results. In some first exemplary results, we have observed that the PDF of the intercell interference reveals important properties of cellular behavior. The capability of interference averaging in Random OFDMA is comparable to WCDMA, hence a similar cellular performance can be expected. The extension of this framework to other techniques such as distributed/localized FDMA or OFDMA with frequency domain scheduling (instead of "random") is straight forward. Introducing effects of link adaptive scheduling and adaptive modulation is more complicated, however possible in principle. The impact of hard/soft handover methods can also be incorporated. Finally, it will be important to consider different assumptions on the traffic model, as well as on user fairness. Work on those extensions is ongoing and will be presented in the future.

Applying equivalent considerations to the downlink is also ongoing. There are some fundamental differences to the uplink. In particular, the interference is not induced at a single location (i.e. at the BS antenna) and is therefore not the same for all users. Instead, the statistical properties of the interference will be conditioned on the location of the users. Additionally, there is a common budget of transmit power in downlink, in contrast to individual power budgets in the uplink. So the fairness issue will be much more complicated. Nevertheless, the principles of the statistical evaluation are exactly the same as described here for the uplink.

Careful description of statistical intercell properties already provides valuable insights into and sharpens the comprehension of cellular access schemes. In addition, intercell PDF's could be plugged into simple single cell simulations, which will give performance figures taking into account the cellular behavior. This will not replace system level simulations, but it will definitely allow for early assessment of future access schemes, or tighten parameter space for the much more exhaustive real-world simulations.

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