Cooperative Antenna Concepts for Interference Mitigation

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ABSTRACT

For future cellular mobile radio systems optimum interference mitigation is one of the key challenges. Cooperative antenna systems promise significant performance gains with respect to throughput, capacity and coverage, but they are difficult to realize in practical systems. Major challenges are channel estimation to many base stations (BS) with high accuracy and data exchange between tightly coupled BSs with low delay. In practical systems cancellation of a limited number of interferers is reasonable, while measurements as well as simulation results show that 40 to 50 interferers might contribute significantly to the resulting interference. For this reason in this paper the interference floor is investigated in more detail as well as a novel combination of interference coordination - reducing the interference floor – with cancellation of a few geographically nearby interferers is proposed.

1 Introduction

Interference mitigation is one of the most promising but also challenging topics for future evolution of mobile cellular radio systems. Especially for urban micro-scenarios interference might easily degrade spectral efficiency by a factor of 3 or even more, as will be shown in this paper.

Cooperative antenna (COOPA) systems, if applied to all base stations (BS) in a given area, provide probably optimum interference mitigation [2] where overall capacity might exceed that of isolated radio cells. COOPA is a multi user multiple input multiple output (MU-MIMO) system, where for all BSs a combined processing is done at a single central unit (CU), which has to be connected to all BSs over fast and low delay data links. As shown e.g. in [2] linear or non-linear pre-processing like zero forcing (ZF), minimum mean square error (MMSE) or non linear transmit zero forcing (NLTxZF) might be applied for the downlink (DL) direction.

Challenging for COOPA is the channel estimation for a high number of involved radio links with high accuracy. Additionally there is a strong trend - e.g. in 3GPP UTRAN long term evolution (LTE) [1] - for flat network architectures, as this leads to cost efficient and simple deployments. For this reason a CU as well as the fast interconnection of BSs is a challenge for most practical systems.

In [2] we proposed a distributed over the air concept for COOPA systems, which avoids the need for a CU and interconnection of BSs.

In parallel to this concept as a further approach and promising alternative here a suitable combination of semi static interference coordination schemes with intra BS cooperation and cancellation of one or two additional interferers is presented and analyzed.

As an additional assumption antenna tilting is taken into account as usually applied also for 3G systems with good effect.

Another well known option to reduce inter cell interference - i.e. the usage of MIMO for beam-forming - is beyond the scope of this paper, even so the here applied simulator has already been used for analysis of up to 8 BS antennas per sector.

The basic system concepts in mind for this analysis are LTE like systems even so here not all features of LTE have been implemented for simulation.

In chapter 2 the typical interference floor is characterized based on measurements and simulations, chapter 3 presents the novel COOPA in combination with coordination, while chapter 4 gives some first simulation results. Chapter 5 concludes the paper.

2 INTERFERENCE FLOOR

For multiple access inter cell interference (IF) mitigation or avoidance in cellular networks there exist a number of proposals. A classical approach is to define a suitable frequency reuse or to apply reuse partitioning [3]. A more advanced technique is IF-coordination which will be described below.
Cancellation of some strongest interferers is very useful, but as will be shown, the residual IF-floor limits the performance gains for reasonable numbers of cancelled interferers. Especially there is a big performance gap to full cooperation between all involved BSs, which eliminates inter cell interference completely.

To understand the limitations of each IF mitigation technique and to find optimal combination of each technique as a first step a detailed analysis of the IF-floor in typical cellular radio systems is required.

It should be noted that in the following downlink (DL) of an OFDM based system like WIMAX 802.16e [4] or 3GPP LTE is assumed, but for simplification the interference for a single sub-carrier (SC) is investigated.

The overall interference \( I_j \) for user \( j \) attached to BS \( k \) is defined by:

\[
I_j = \sum_{i \neq k} P_{ij} \cdot L_{ij} \cdot A_{ij} \tag{1}
\]

where \( P_{ij} \) is the transmit power of BS \( i \) to user \( j \), \( L_{ij} \) is the attenuation between BS \( i \) and the user \( j \) of interest and \( A_{ij} \) is the value of the antenna pattern of the BS \( i \) of interest towards user \( j \). The sum runs over all BSs \( i \).

The attenuation \( L_{ij} \) consists generally of three components:

- The pathloss which is given by the user’s distance to the BS. Here we assume a uniform, but random distribution of the users within a cell.
- The shadowing which is typically modeled as a random variable with log-normal distribution.
- Small scale fading which is given by an N-path Rayleigh fading. The distribution becomes a \( \chi^2_{2N} \) distribution with \( 2N \) degrees of freedom.

The value of the antenna patterns \( A_{ij} \) is given by the assumed 70 degree beam pattern using sectorized cells.

In Figure 1 the interference \( I_j \) for a HATA Urban the together with a sectorized cell layout for 57 BSs with 3 sectors per cell and a hexagonal shape per sector has been simulated. Each sector supports 3 mobile stations (MS) in time division multiple access (TDMA) mode, which have been uniformly and randomly placed within the sectors. The sector layout and allocation of BS numbers can be found in Figure 9.

It should be mentioned that the SCME channel model includes a distance dependent non line of sight (NLOS) probability for the radio channels.

In Figure 1 the colors indicate the power of interference from BS \( i \) to user \( j \), where always 3 UEs are allocated to one BS. At the diagonal the color indicates the signal power from the serving BS to the user \( j \) allocated to this BS. The plot shows a snapshot for one special channel realization and user location.

In the plot different areas can be distinguished:

- Around the diagonal elements – area \( a \) in Figure 1 - there is strong IF from adjacent BSs, especially from those with antenna patterns \( A_{ij} \) directing to the own sector.
- This area is followed by an area with relatively weak IF
- A second area with strong IF can be found from second tier BSs, i.e. area \( b \) in Figure 1.

As can be seen in cellular systems a high number of BSs contributes to the overall interference floor. Due to shadowing and different LOS/NLOS conditions also interference from far off BSs will have detrimental effects on the signal to interference and noise ratio (SINR).

The according power distribution of interferes for the simulation in Figure 1 can be found in Figure 2. From this distribution it is obvious that cancellation of one or two strongest interferers might give some substantial performance gain, but then for each additional cancelled interferer the further gain will decrease.

As the interference distribution is of main importance for the definition of a suitable IF-mitigation strategy, a measurement campaign in real world 3GPP UMTS networks has been conducted based on the
The measurement was done based on the common pilot channels, which are transmitted from the BSs with constant power and independent of the load in the cells. The measurement was conducted in Berlin with the routes in Figure 3. The interference power distribution for the strongest interferes for four different mobile network operators (MNO) using different carriers are shown in Figure 4.

In comparison with the simulated IF-distribution following observations are possible:

- Different MNOs seem to apply different deployment strategies. The two upper plots have therefore significant higher power separation between interferers.
- Even the two lower plots with higher interferer density have a higher IF separation than the simulated scenario in Figure 2. As will be shown in the next chapter the reason is most probably due to different antenna tilting strategies.
- While for the higher power interferes the distance is quite large it is getting very small for the low power interferers.

- In contrast to the simulation results only a small number of interferes can be seen. As the received power levels of the different BSs has been measured based on the CPICH channel and the according cell id, there is only a limited measurement power window of about 20dB, defined by the CDMA coding gain. From measurements of the overall receive power a similar IF floor can be deduced as for the simulation results. This floor is just invisible.

**3 COOPA-COOR Concept**

From the above chapter the main challenge for advanced IF mitigation is obvious. Due to the high number of interferers, advanced techniques like IF cancellation of strongest interferers promise some gain, but the gap to the performance for full cooperation between all BSs is still very large.

Unfortunately the cancellation of an interferer is complex and requires typically significant overhead, e.g. due to accurate channel estimation. IF-coordination
techniques like fractional frequency reuse (FFR) have shown promising gains, but are as well far off from the upper bound.

The same is true for antenna tilting which is typically optimized during network planning.

For this reason the cooperative antennas with coordination (COOPA-COOR) concept has been developed, where all three above mentioned techniques are combined, exploiting the main characteristics of each technique in an optimum way. As will be shown below the resulting gain is significant higher than for each technique alone.

COOPA-COOR uses antenna tilting to reduce interferers from second tier BSs. Semi-static or static IF-coordination is used to lower interference from first tier BSs while IF-cancellation is restricted to very few interferers from adjacent BSs. This strategy helps to lower the overall interference floor so that only very few strongest interferers remain, which are cancelled.

As the overall interferers floor is small due to antenna tilting and coordination IF cancellation gives now a big jump in overall performance.

In Figure 2 two different characteristics can be distinguished, i.e. the larger five interferers have a power separation of roughly 2 dB while the residual 52 interferers have a separation of roughly 0.5 dB.

Let us assume 57 interferers with equal distance of 0.5 dB between two adjacent interferers, where the 4 strongest interferers are cancelled. Note, the power of the strongest interferer $I_{FS}$ belongs to the serving BS.

The overall cancellation gain will be limited by the power of the residual interference floor $IF_{floor}$. $IF_{floor}$ can be calculated by using partial sums for the following geometrical row:

$$q(0.5 \text{ dB}) = 10^{0.5 \times 10} = 0.9$$

$$IF_{floor} / I_{FS} = \sum_{n=0}^{57} 0.1 q_n = (q^5 - q^57) / (1 - q) = 0.5$$  (2)

As can be seen the summation of a high number of relatively small values results in a high IF floor which limits the cancellation gain of even 4 interferers to about 3 dB.

As cancellation of 50 or more interferers is impractical other means have to be found to achieve promising gains, justifying the relative high effort for IF cancellation.

In the following antenna tilting, IF-coordination and cancellation is combined and it will be show that the combination outperforms the gain of each technique alone significantly.

### 3.1 Antenna Tilting

Antenna tilting is commonly used in today’s networks and has proven to be very efficient. Typically the antenna tilt is adapted to the cell size so that the power in the own cell is maximized while interference into adjacent cells is reduced as far as possible. For f-reuse 1 systems often a compromise has to be found to avoid coverage holes.

Figure 5 depicts a typical BS antenna pattern. Due to a large number of antenna elements these antennas have vertical half power beam width of a few, e.g. 6° and front-to-back ratios of 20-30 dB. Antenna tilts up to 10° might be applied, which leads to significant increasing power reduction for increasing distance which is applied to each BS.

A comparison of Figure 6 with Figure 1 reveals for an antenna tilting of 7° a significantly reduced IF floor for second tier BSs (blue areas).

From Figure 7 the simulated IF power distribution after tilting reveals a much larger spreading of the IF power after tilting.

For UMTS WCDMA systems gains in the order of some 10% have been reported.
3.2 Semi static IF-Coordination

First tier BSs are affected only slightly by antenna tilting if full Rx power to the cell edge is intended so that there are still a high number of interferers which are too many to be cancelled in practical systems.

For this reason an additional technique is required to reduce first tier interferers. Fortunately with static or semi-static IF coordination – also called fractional frequency reuse (FFR) or coordinated power selection (CPS) – a suitable technique is available. In Figure 8 the basic FFR concept of using different frequency bands for cell edge (CEU) and cell center users (CCU) is shown. For each f-band statically or semi-statically a maximum Tx power is defined. This avoids that adjacent cells schedule simultaneously CEUs with maximum power on the same resource unit, which would lead to a collision.

Based on relative SINR measurements the MSs are scheduled as CCUs or CEUs, i.e. CCUs with good radio conditions are scheduled into the low power frequency subbands while CEUs are scheduled as far as possible into the high power bands.

IF coordination is promising, especially due to its very easy implementation as neither signaling nor channel estimation is required.

3.3 IF cancellation clusters

In case of IF cancellation the coordination pattern of Figure 8 is not useful as it would reduce IF for adjacent cells which can be more easily avoided by cancellation. For this reason a suitable modification can be seen in Figure 9 where exemplary clusters of 3 cells – indicated by same color - are having the same CPS frequency band allocation. Due to this 3 cell clusters the minimum distance between cells using the same CPS allocation has been increased compared to Figure 8, reducing the collision probability.

The clusters using the same CPS pattern will typically interfere strongly which each others. For this reason in each cluster IF-cancellation has to be applied, which is realistic as the number of interferers which have to be cancelled is small. Without inter BS cooperation following techniques can be applied for IF-cancellation:

a) intra BS cooperation
For each site with 3 BSs the baseband processing can be done commonly as the BS signals join in one housing. This allows applying classical cooperative transmission or reception techniques like joint transmission or joint detection [5]. This
results in a MU-MIMO scheme even so each BS as well as MS might have only one single antenna element.

Figure 9: Simulation scenario and coordination pattern

b) Interference rejection combining at MS
   As inter BS communication is not assumed cancellation of a further interferer might be done by interference rejection combining at the MS. For this purpose it is assumed that each MS has at least 2 antenna elements and can estimate the radio channel to the adjacent BS based on common pilot signals.

c) BS nulling
   If a 5th interferer should be cancelled without inter BS cooperation BS nulling might be applied. For this purpose the BS has to get information about the generated interference into adjacent radio cells by feedback from the actually active interfered MS. This information allows the BS to adapt its Tx antenna pattern so that interference to the interfered MS is reduced or nulled. This is definitely a challenging technique regarding channel estimation and error-free feedback of the information to the adjacent BS.

The above described techniques b) and c) assume multiple antenna elements at BSs as well MSs. The underlying idea is to use the spatial degree of freedom given by the additional antenna elements for IF cancellation instead of spatial multiplexing or diversity gains. The MIMO mode of operation might be adapted depending whether MS peak data rate, robustness or overall system throughput should be maximized, but often for CEUs the performance gain due IF mitigation will outperform other MIMO gains.

4 SIMULATION RESULTS

The above described concept has been simulated to check the achievable gains. The simulations are adapted to the parameters of LTE-like systems as far as possible, even so many features like e.g. frequency dependent scheduling are not implemented yet.

4.1 Simulation setup

For the simulation a 57 sectors, arranged in 19 cellsites has been used to avoid cell border effects. Hence, each cell site has 3 sectors, looking to east, northwest and southwest. Only the performance of the center cell has been analyzed.

Only one MS per sector is active within one timeslot to avoid intra cell interference. The timeslots have a length of 0.0011 seconds.

For the default setup SISO channels are used, i.e. each BS as well MS has only one antenna element, but as explained above for IF-cancellation at least one additional MS as well as BS antenna is assumed. To assess possible performance gains of the scheme the proposed IF-cancellation techniques have not been applied yet. Instead different IF-cancellation values are assumed independent of the applied techniques which are for further study. No BS power control is being used.

Further parameters can be found in Table 1. The antenna tilt of 7° is quite high but realistic and has been chosen due to the small cell sites.

<table>
<thead>
<tr>
<th># of BS antennas per sector $n_T$</th>
<th>1 (2nd AE used for IF cancellation)</th>
</tr>
</thead>
<tbody>
<tr>
<td># of MS antennas $n_R$</td>
<td>2 (2nd AE used for IF cancellation)</td>
</tr>
<tr>
<td>Antenna tilt</td>
<td>7°</td>
</tr>
<tr>
<td>BS height</td>
<td>35m</td>
</tr>
<tr>
<td>MS height</td>
<td>1.5m</td>
</tr>
<tr>
<td># of sectors</td>
<td>3</td>
</tr>
<tr>
<td># of MSS</td>
<td>400</td>
</tr>
<tr>
<td>Max MS power</td>
<td>46dBm</td>
</tr>
<tr>
<td>Channel model</td>
<td>HATA Urban (Fig 10)</td>
</tr>
<tr>
<td></td>
<td>3GPP SCME (spatial channel model extended)</td>
</tr>
<tr>
<td></td>
<td>urban macro [1] (Fig 11)</td>
</tr>
<tr>
<td>radio channels</td>
<td>basically uncorrelated</td>
</tr>
<tr>
<td>CPS f-bands</td>
<td>3</td>
</tr>
<tr>
<td>CPS power levels</td>
<td>0 / -6 / -9dB (Fig 10)</td>
</tr>
<tr>
<td></td>
<td>0 / -2 / -10dB (Fig 11)</td>
</tr>
<tr>
<td>IF cancellation</td>
<td>20dB</td>
</tr>
<tr>
<td>Inter Cell distance</td>
<td>700m</td>
</tr>
</tbody>
</table>
Minimum distance to BS | 35m  
mobile speed | low (< 16kmh)  
Channel estimation | perfect  
RF frequency | 2 GHz  
bandwidth | 20 MHz  
resource allocation | Localized

**Table 1: main simulation parameters**

### 4.2 Simulation results

Figure 11 gives typical results for the simulation setup according to the above paragraph for the urbanHATA channel model. For assessment the theoretical achievable throughput CDFs of a conventional $f_{\text{reuse}} = 1$ system are compared with those where either tilting, CPS, IF-cancellation or any combination of these techniques has been applied. Each technique by its own gives some similar gain as can be seen from the red, green and violet line which in the order of several 10%. The combination of tilting plus CPS results in some gain significantly outperformed from the combination of tilting plus cancellation.

The by far highest gain is achieved for the combination of all techniques, i.e. tilting, CPS and IF-cancellation. At the 50% CDF value for a default $f_{\text{reuse}}=1$ scenario the throughput is due to heavy interference very small, i.e. about 2Mbit/s. For the optimum approach 80 Mbit/s - i.e. 4bit/Hz/s – can be achieved. The 5 percentile users at cell edge exhibit similar performance gains, giving best case almost 1bit/s/Hz spectral efficiency.

The reason that the combination of all techniques is so much better than each technique alone is as explained above. Tilting can reduce the second tier while CPS will reduce the first tier IF floor. Without IF-cancellation the remaining strongest interferes limit the performance gain for these techniques. For IF-cancellation without tilting and/or CPS it is the opposite way, i.e. the remaining IF floor limits the performance.

### 5 CONCLUSIONS

Promising performance gains have been demonstrated for a suitable combination of IF-cancellation of few strongest interferers from adjacent cells and sectors with interference coordination and antenna tilting.

The combination of all techniques outperforms the application of each technique alone significantly and results in promising spectral efficiencies in cellular mobile radio systems.

For IF-cancellation techniques like intra-BS cooperation, interference rejection combining at MSs with 2 antenna elements and IF nulling by antenna pattern adaptation is proposed. Channel estimation, especially for IF nulling, will be a major challenge for real systems. It has not taken into account in this paper, but is analyzed by us in parallel projects.

### REFERENCES

[1] 3 GPP TR 25.814, “Physical Layer Aspects for Evolved UTRA (Release 7)”, version 0.1.1, after RAN1 Adhoc on LTE (R1-050682), Sophia Antipolis, France, 06 2005