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Interference mitigation by distributed beam forming optimization

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Abstract – Inter-cell interference is a major issue in OFDMA networks. One approach to reduce the amount of interference is to use beam forming antennas. Further interference mitigation is achieved if neighbor base stations coordinate the directions of their beams. This paper presents a novel distributed interference coordination algorithm using main-lobe steering beam formers. Our algorithm does not require any explicit signaling between base stations. Also, it does not require any additional channel measurements to be signaled to the base stations besides those already performed for basic operation. Our evaluations show that significant performance gains can be achieved even with non-greedy traffic.

Index Terms – Interference coordination, beam forming antennas, COMP

1. Introduction

1.1 Motivation

For cellular radio access networks, the ever growing demand for capacity makes spectrum a scarce resource. To use the available spectrum as efficiently as possible, these networks use the same frequency resources in all base stations (reuse 1) and try to maximize the spectral efficiency. In reuse 1 scenarios, the achievable spectral efficiency is usually limited by the interference from neighboring base stations, whereas noise does not play a significant role. Therefore, the goal of most interference coordination mechanisms is to reduce the interference from neighboring cell sectors on the transmissions in the current cell sector. Especially for users at the cell edge this improves the channel quality.

We consider the downlink of cellular OFDMA networks such as IEEE 802.16e WiMAX or 3GPP LTE. We assume the base station to be equipped with multiple antennas that are used in combination with main-lobe steering beamformers.

1.2 Related Work

The classical approach to handle interference is frequency reuse. It partitions the spectrum and uses the same partition in spatially disjoint cell sectors, only [1]. Fractional frequency reuse is an extension of the classical scheme. It splits cells into different areas, defines primary and secondary resources for these areas, and assigns primary and/or secondary resources to terminals. The so-called "soft reuse" schemes further reduce transmission power for secondary resources. The partitioning of the resources is usually done during network planning or in a semi-static way on a large time scale. Higher gain is achieved with more dynamic schemes, which adapt to traffic variations and user distribution [2].

Another approach is feasible in cases where the power of an interfering signal is sufficiently high. Then the receiver can also decode the interfering signal and subtract it from the desired signal. In addition, modern interference reduction techniques also use multi-antenna arrays to distinguish the signal sources. When the base stations are equipped with such antenna arrays, the spatial domain can be utilized to avoid interference at the transmitter side [3]. The coordination of transmission modes of multiple base stations is called *coordinated beam forming* in the 3GPP specifications [4].

In this paper, we investigate an interference coordination scheme for the downlink of an OFDMA mobile communication system, operating with main-lobe steering using four antenna-elements at the base station and a single antenna at the mobile station. We assume that the base station always directs the beam to the targeted mobile station (see Fig. 1). Because each neighboring base station serves multiple mobile stations simultaneously, the beam directions differ for resources assigned to different mobile stations. Therefore, the interference a mobile station receives depends on the resource allocation of its neighbors. Our algorithm strives to minimize the interference by optimizing this resource allocation.

Fig. 1: Principle of coordinated beam forming.

Previous work has shown that large gains can be achieved by joint optimization of the scheduling of multiple base stations [5], [6]. However, the algorithms investigated there are not fully distributed and are hard to implement in a real network.

Our algorithm works fully distributed and without explicit communication among the base stations. Furthermore, it does not require the mobiles to measure each components of the interference separately. Instead, the base station must only know the sum of the interference power and the power of the desired signal measured by the mobile station. Our algorithm was developed for a 3GPP LTE system.

An algorithm similar to the presented one is used in [7]. There, interference in a 60GHz WPAN is mitigated by changing the set of used resources if the transmission is jammed by interference. However, the system presented in that publication does not use all resources at the same time. In contrast, our algorithm is applied in a reuse-1 scenario with full transmit power in all cells. In [8], the authors describe an interference coordination algorithm for LTE networks. Their approach uses precoding matrices restricted by a codebook. Each mobile station measures the channel to the neighbor cells and signals which precodings the neighbor cells shall avoid. In contrast to our algorithm their algorithm requires additional measurements by the mobile stations and more signaling between mobile stations and base stations as well as between base stations.

The remainder of this document is structured as follows. The following section presents the coordination algorithm. Section 3 describes the applied evaluation methodology. The coordination algorithm is evaluated as a function of several parameters in Section 4. In addition, the influence of the variability of the traffic is investigated. Section 5 concludes the paper.

2. Distributed Interference Coordination Algorithm

Fig. 2: Principle of the coordination algorithm

The overall goal of the presented algorithm is to improve the system's capacity by using beam forming and by directing the beams towards the targeted receivers in a coordinated fashion. Steering the beams provides a degree of freedom, which we exploit to minimize the overall interference. Since the geographical position of the mobiles varies over time, the beams have to be adjusted continuously. We assume non-greedy traffic, which imposes additional boundary conditions.

2.1 Assumptions

We assume that all base stations use the same partitioning of the available radio resources into orthogonal units.

We assume that it is not possible to measure the interference relations between mobile stations directly. This means that a mobile station can measure the sum of interference it receives, but it cannot see how much each of its neighbors contributes to this sum. We assume that the system is interference limited and therefore thermal noise does not have a significant influence.

We assume that each mobile station can measure the interference power as well as the SIR (signal to interference ratio). Each coordinated station reports these values to its base station. In typical systems this information can be derived from values that are measured and reported anyway: The CQI (channel quality indicator) corresponds to the SIR. By combining the CQI with the RSSI (signal strength indicator) the sum interference can be obtained. We assume that these values are only measured and reported for the resources on which data was transmitted to this mobile station.

For simplicity, we further assume that the same number of mobile stations is served in each sector and each mobile station gets the same amount of resources. Therefore, we also have a defined and constant operation point of eight active mobile stations per sector. An extension to an arbitrary number of users is straight-forward.

Since the algorithm is designed for low measurement overhead, we assume that frequency selective scheduling is not used. We deal with logical channels that are created by frequency diverse permutation of sub-carriers to even out fast fading channel variations.

2.2 Key idea

The algorithm tries to keep the resource assignment over multiple frames as constant as possible. In the example in Fig. 2, this is the case from TTI1 to TTI3 where the resource assignment does not change. When the interference situation becomes too bad, the resource assignment is changed. In the example in Fig. 2 this is the case for the purple (third) mobile station after TTI3. Keeping the resource assignment as constant as possible is important to allow other base stations to assess the interference that their mobile stations have to expect. In contrast, improving the interference situation is only possible by changing the resource assignment. Obviously, these two goals are conflicting, and an important part of the algorithm is the decision when to change the resource assignment. In the following frames, neighboring base stations can adapt to this decision. That way, the entire system strives to a better point of operation.

2.3 Algorithm

To enable a base station to decide whether it should keep or change the resource assignment, each mobile station measures the current channel situation and reports it to its base station. The base station then evaluates the situation using a cost function. Based on the cost and a randomization function, the base station decides whether to change the current resource assignment or not. To change the resource assignment, another active mobile station of the same sector is selected randomly and the resource assignment of both mobile stations is swapped. See algorithm 1 for a pseudo code representation. The following paragraphs describe the building blocks in detail.

Interference monitoring: For each of its mobile stations the base station obtains a measurement of the current SIR and interference sum. Since the resource assignment of this base station and its neighbors is kept as constant as possible, this measurement constitutes a good prediction for the SINR and the interference in the following TTIs.

Cost Function: The cost function aims to describe how “good” a given situation is for a mobile station. It is evaluated for each mobile station and is a function of the logarithmic SINR γ (in dB) and the interference sum i (in dBW/Hz). A lower value of the cost function $c(\gamma, i)$ represents a better situation.

Four different cost functions have been evaluated and compared:

$$\begin{aligned}
&\text{CONST}: && c_{\text{CONST}}(\gamma,i) &&= 0 \\
&\text{IFSUM}: && c_{\text{IFSUM}}(\gamma,i) &&= i \\
&\text{SIR}: && c_{\text{SIR}}(\gamma,i) &&= -\gamma \\
&\text{IF-SIR}: && c_{\text{IF-SIR}}(\gamma,i) &&= i-\gamma
\end{aligned} \tag{1}$$

The first option (CONST) is used as a reference, as it does not react to the actual interference situation but changes a resource assignment by random.

Randomized resource assignment: Instead of deciding whether to change a resource assignment by using a deterministic threshold, we apply a randomized threshold to avoid oscillating swap sequences. The higher the value of the cost function, the higher the probability to change the current situation. A simple s-shaped curve $s(x)$ is used to calculate the probability of changing the resource assignment.

$$s(x) = \begin{cases} 0 & x \le \alpha-\delta \\ 2\left(\dfrac{x-\alpha-\delta}{2\delta}\right)^2 & \alpha-\delta < x \le \alpha \\ 1-2\left(\dfrac{\alpha-x+\delta}{2\delta}\right)^2 & \alpha < x \le \alpha+\delta \\ 1 & \text{else} \end{cases} \tag{2}$$

Based on the calculated probability an uncorrelated Bernoulli experiment takes the decision. The threshold value α and the width of the s-curve δ are parameters of the algorithm. Their influence is evaluated in section 4.

Algorithm 1: Interference mitigation algorithm

```
for all TTI do
    for all mobile station do
        Obtain reports of previous TTI (γ and i)
        Calculate cost function: c(γ,i)  and change probability p := s(c)
        if (random value u(0,1) < p) then
            Choose pivot partition and perform change
        end if
        Schedule to assigned resource partition
    end for
end for
```

3. Evaluation Methodology

The algorithm has been evaluated by system level simulation of an LTE-like system. The simulator is based on the IKR SimLib [9]. In this section, we describe the simulation model and the methods used to evaluate the algorithms.

Our scenario consists of 19 sites and three sectors per site, placed on regular hexagons. To avoid border effects, wrap-around is used. The mobile stations are distributed uniformly over the whole scenario and move with a constant speed of 10km/h. They use a single isotropic antenna without antenna gain. Each mobile is served by the base station with highest signal strength. Data is transmitted in downlink direction by a scheduler as described in section 2.3. Uplink is not taken into account and is assumed to work without delay or packet loss.

The channel model consists of a pathloss model according to [10] and of a Gudmundson slow fading model as in [11]. Table 1 gives the parameters of the slow fading model. We do not model fast fading, because the algorithm is assumed to be used with a frequency diverse permutation of the systems resources. Each sector is equipped with a main-lobe steering beamformer, consisting of a linear array of 4 sector antennas. These are modeled by a gain pattern derived from measurements of a real setup as described in [12], assuming pure line-of-sight for the multi-antenna effects. For each resource block, the main-lobe of the antenna array is pointed at the receiving mobile station. The accuracy of the beam is 1° and ideal tracking of the mobiles is assumed.

Table 1: <tab=1>Simulation parameters.

To model the variance of the traffic which influences the performance of the algorithm, we use an on-off traffic model. During the ON phase, we assume that a mobile station always has data to send. The mean length of the ON phase is set to 0.2s if not stated otherwise. The total number of mobile stations per sector depends on their movement and is 1000/57=17.5 in average. For simplification, we assume that each sector always contains eight active mobile stations. Our traffic model is designed such that the number of active mobile stations remains constant. This means, that if the ON phase of one mobile station in a cell ends, one of the previously inactive mobile stations will be switched on. In addition, if there are already eight active users in a cell and another mobile station handovers to this cell, one of the active mobile stations is switched off. Because of the slow movement of the mobile stations, the influence of the additional switching caused by handovers is small.

For the calculation of the channel quality (SINR) and the spectral efficiency, the system bandwidth of 10MHz is divided into eight equally sized sub-bands. The scheduler assigns one of these allocation units to each mobile station. The SINR value is calculated for each allocation unit according to the channel model and the scheduling of the other base stations. Based on the SINR, a transport format is selected from a set of 27 LTE transport formats, such that the block error probability does not exceed 10%. Block errors are modeled by BLER tables. Retransmissions, as usually implemented by an automatic repeat request (ARQ) protocol, are not modeled.

The overhead of three OFDM symbols for signaling, the cell specific reference symbols for a single antenna port, and the terminal specific reference symbols is subtracted from the capacity of each transmission. For each active mobile station, the throughput measurements sum up the capacity of the successfully decoded transmissions over an interval of 10ms. The 5% quantile of the cumulative density function (CDF) of these spectral efficiency values is used to evaluate the cell edge throughput. For each parameterization, 30 independent drops are simulated with 4000 frames per drop. The first half of each drop is ignored to get rid of transient effects.

4. Performance Evaluation Results

4.1 Influence of different cost functions

Choosing a suitable cost function to determine whether to change the resource assignment has a high influence on the performance of the coordination algorithm. Fig. 3 shows the spectral efficiency of the cell edge and the entire sector for the cost functions described in section 2.3. As a reference, the cost function CONST shows the performance of pure random behavior. As expected, there is no coordination gain in this case. The algorithm achieves the highest coordination gain when using the IF-SIR cost function, which is about 0.7dB in SINR. Using either the IFSUM or the SIR cost function provides a lower coordination gain.

Fig. 3: Sector throughput and edge throughput for different cost functions and α parameter.

4.2 Influence of randomization

The presented algorithm employs a randomization of the swap decision to prevent staying in local minima. The parameters α and δ determine the shape of the s-curve and, thus, the randomization process. α determines the cost threshold while δ determines the sensitivity to cost value changes. Fig. 4 shows the average SINR as a function of α and δ. If δ is too low, the s-curve has a narrow transition range and therefore the adjustment of α must be very precise, making the algorithm less robust in practice. A too large δ reduces the coordination gain and makes the algorithm slower for varying traffic. We chose δ = 20dB as a good compromise. One can observe that the coordination algorithm achieves good results for multiple combinations of α and δ. All these combinations have in common that the average swap probability is at 2-5%.

Fig. 4: SINR for different widths of the s-curve δ.

4.3 Influence of On-Off-traffic

Finding a scheduling decision in a decentralized fashion takes time. Thus, this coordination algorithm is sensitive to traffic fluctuations. Fig. 5 shows the dependence of the SINR gain to different ON phase durations. One can observe that larger ON times allow for higher coordination gains. The time it takes the coordination algorithm to settle can be estimated from the frame duration of 1ms and the average swap probability of 2-5% at best operation points. One iteration is in the order of magnitude of 20-50ms. Assuming that reaching a good resource assignment takes several iterations, the algorithm needs several hundred ms to settle. Fig. 6 shows the autocorrelation function of the points in time of the swap decision and supports that assumption, since most energy is located in the area from 0-1s. In the autocorrelation plot, 1 is the average swap probability. A value bigger than 1 means, that *n* frames after a swap the chance for an additional swap is higher than average and vice versa.

Fig. 5:	SINR for different mean ON times of the ON/OFF traffic model.
Fig. 6:	Effect of the α parameter on convergence behavior.

5. Conclusion

We presented a distributed interference coordination algorithm which works without explicit communication among the base stations. The coordination is performed implicitly by the use of channel measurements by the mobile stations. Nevertheless, our algorithm does not require additional measurements besides those already available in typical systems. The algorithm tries to keep the resource assignment constant as long as it is reasonable, which improves the channel estimation quality.

Interference coordination approaches that assume to have global knowledge about interference relations in [13] can achieve 60% gain in cell throughput and 165% gain in sector edge throughput. Compared to this class of approaches, the achievable gains of the presented interference coordination algorithm is lower (5.7% gain in cell throughput, around 10% gain in edge throughput). Yet, it requires much less of the knowledge, measurement, and reporting overhead and thus is implementable in real-world systems. Also, the given throughput gains are evaluated with a non-greedy traffic assumption.

An additional performance gain could be achieved by using cost functions which take into account the maximum possible channel quality for a mobile station in the given situation. A low amount of signaling between the base stations could increase the convergence speed. Investigating these possibilities will be subject to further studies.

We investigated the algorithm in a scenario where the transmissions of all users are coordinated and all available resources are used. However, the proposed resource assignment scheme cannot be combined with other scheduling techniques, such as frequency selective scheduling. The ideal scheme with which a mobile can be served depends, besides others, on the speed of the mobile and the variability of its traffic. In a real world application, only a part of the resources would be coordinated with the proposed algorithm and other users could be served on the remaining resources without coordination.

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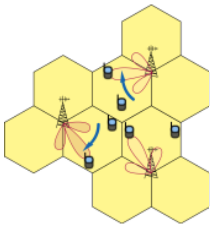
Table 1: <tab=1>Simulation parameters.

Frame duration	1ms	System bandwidth	10MHz
Transmit power	46dBm	Inter-site distance	1000m
Mobility model	Random Direction	Mobile speed	10 km/h
Mobile users	1000	Mobile users	8
Pathloss model	COST 231 modified Hata [10]	Shadowing model	time-correlated Gudmundson (σ=8dB, inter site corr.=0.5, corr. dist.=50m)



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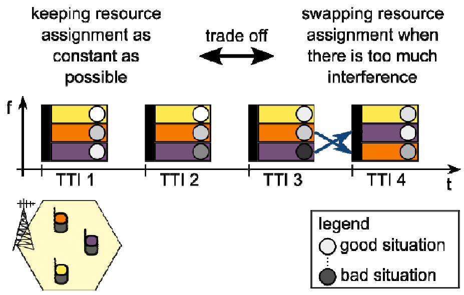

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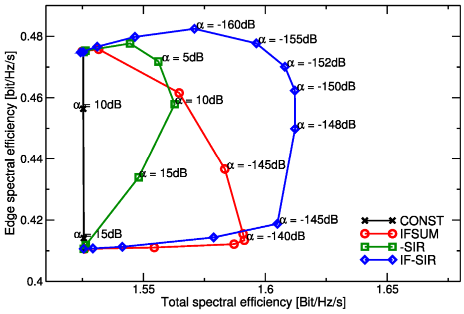

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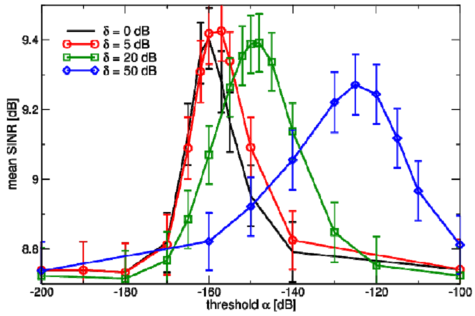

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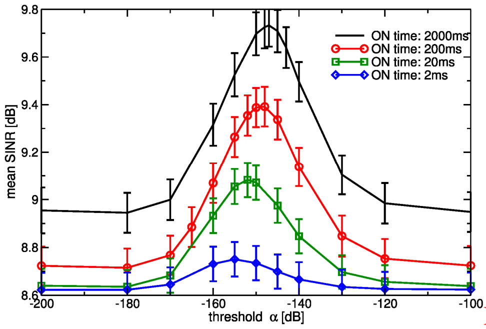

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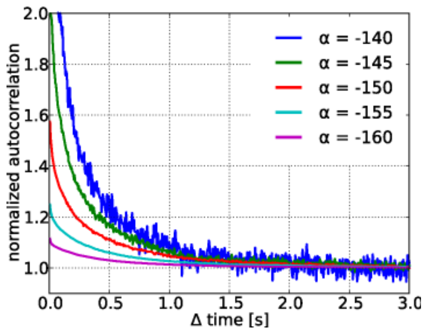

Fig. 6: