Practical Challenges of IA in Frequency

Technical Report TR-SEEMOO-2013-01
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Abstract

Interference Alignment (IA) is a promising technique at the physical layer which allows to increase the Degree-of-Freedom (DOF) of a communication by aligning all interfering signals into the same dimension, while the desired signal lies unaffected in an orthogonal dimension. IA has been widely studied in theory, but only limited practical work exists, since it poses significant challenges for real-world deployments. In this report, we study issues which are key to enable IA in practice.

1 Introduction

IA is an information-theoretical approach proposed as recently as 2008. Essentially, IA allows to overcome the "cake-cutting" dilemma, i.e., the more users, the less share of the "cake" each one gets, where cake stands for wireless resources. In other words, given K interfering users, typically each one gets a $1/K$ share of the resources. IA allows each user to get $1/2$ of the resources, i.e., each user gets half the cake, no matter the number of users.

This surprising and highly interesting result was shown by Cadambe and Jafar in [1]. The key principle behind IA is to align all interfering signals into the same dimension, while the desired signal lies unaffected in an orthogonal dimension. Hence, the number of interferer nodes can be arbitrary, as interference just adds to a dimension the receiver ignores anyhow. However, in order to achieve "half the cake", channel coefficients must match specific characteristics which are typically not fulfilled in practice. Still, IA can work also with random channels assuming Channel State Information (CSI) at the transmitters and under a certain penalty in form of symbol extensions, which essentially means that IA is done over multiple consecutive symbols affected by different channel coefficients. In the time domain, this translates into the necessity of knowing future channel coefficients, which strongly limits its practicability. On the contrary, in the frequency domain estimates for multiple carriers can be obtained in parallel. Moreover, it is directly applicable to the vast majority of todays wireless access networks, which are based on Orthogonal Frequency-Division Multiplexing (OFDM) and thus allow for IA over multiple subcarriers on their current physical layer. Due to this wide applicability, in this report we focus on practical issues to enable IA in the frequency domain. Specifically, we analyze the following topics:

- Impact of heterogeneous signal-to-noise ratios (SNRs) regarding the nodes involved in IA, instead of the common assumption of all nodes having similar channel quality.
- Level of CSI detail required for IA to work. This is a key trade-off, since coarse CSI degrades IA performance, while too detailed CSI causes unnecessary overhead and thus reduces gains.
- Feasibility of providing robust CSI feedback to IA transmitters, i.e., we analyze how bit errors in over-the-air feedback affect the performance of IA.

The rest of this report is organized as follows. In Section 2 we explain how our assumptions and system model, which specify how our system works. Next, in Section 3 we study the case of heterogeneous SNRs. In Section 4 we determine the level of detail required for CSI feedback in an IA system. After that, we discuss the robustness of our scheme to send CSI back to the transmitters. Finally, in Section 6 we summarize our conclusions on the aforementioned practical issues.

2 System Model

We assume a wireless access network with 3 access points (APs) and 3 mobile stations (MSs) using OFDM with N subcarriers. Each AP sends unicast data to one MS. Transmitter-receiver pairs are fixed, i.e., each AP is always associated to the same MS on all subcarriers. We use IA with symbol extension in the frequency domain as described in [1] for the downlink. Essentially, this means that all APs transmit simultaneously using all subcarriers, which are grouped into groups of three. We call each group of three subcarriers a combination. Using IA, the three APs can transmit four symbols to the three MSs using only one combination of three subcarriers. In other words, IA allows us to achieve $\frac{4}{3} = 33\%$ gain compared to standard OFDM, which can only transmit one symbol per subcarrier. IA requires CSI at the transmitters, which is used to calculate precoding vectors. These vectors ensure that the interfering signals from each AP on its non-associated MSs are aligned on a dimension orthogonal to the signal intended for each MS. We measure the aforementioned CSI using pilots and send in back to the transmitters over-the-air.

3 Heterogeneous SNRs

In our first experiment, we study by means of simulation the impact of heterogeneous SNRs on IA in the frequency domain. More precisely, we generate a network with three APs at fixed locations and three MSs at random locations. The APs are located on the vertexes of an equilateral triangle, which has an area $A_D = 100\ m^2$ and is centered on the square simulation area ($A = 900\ m^2$), as shown in Figure **??**. We consider a path loss exponent of $\alpha = 2$ and set the SNR to 70 dB at one meter distance from the APs.

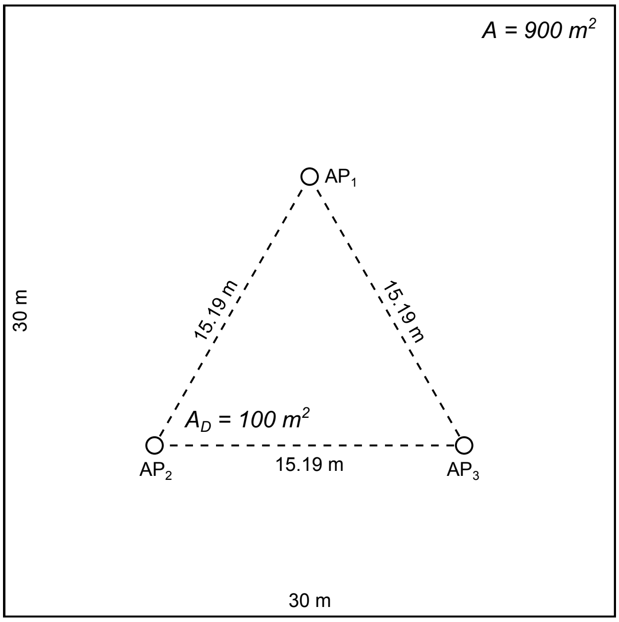

Figure 1: Setup for our experiment with heterogeneous SNRs. MSs are deployed randomly in area *A*.

Under the aforementioned assumptions, nodes have similar SNRs to each AP only when they fall inside the equilateral triangle. To assess how this impacts performance, we introduce a hot spot factor f_{HS}, which models the probability P_D of nodes falling inside the triangle, as shown in Equation 1.

$$P_D = \frac{A_D \cdot f_{\mathrm{HS}}}{(A + A_D \cdot (f_{\mathrm{HS}} - 1))} \quad (1)$$

In other words, when $f_{\mathrm{HS}} = 1$, MSs fall with equal probability inside and outside the triangle. On the contrary, for $f_{\mathrm{HS}} = \infty$, all MSs are inside the triangle. We simulate this setting for $f_{\mathrm{HS}} \in [1; 250]$, which translates into $P_D \in [0.111; 0.969]$. The results are depicted in Figure 2, where we show the gain of IA and IA+OFDM compared to an Orthogonal Frequency-Division Multiple Access (OFDMA) scheme which allocates each subcarrier to the best AP-MS pair available. IA+OFDM is a combination of IA and OFDM which only uses IA on subcarriers which provide sufficient channel quality in terms of SNR, resorting to OFDM otherwise. For both IA and IA+OFDM, the simulation shows that similar SNRs to all APs are beneficial for IA. As soon as the probability P_D raises, gains increase significantly. It stabilizes at about $P_D = 80\%$, since from that value on MSs fall with high probability in the triangle and SNRs are similar. Hence, we conclude that IA works best when each MSs has high and similar SNRs to all APs.

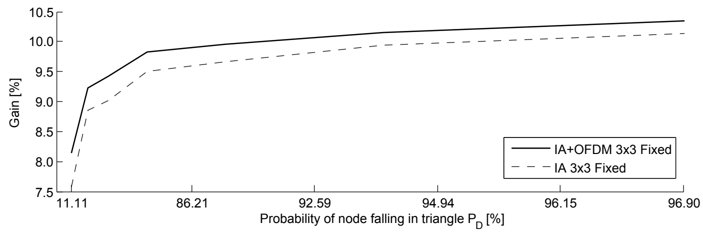

Figure 2: IA gain compared to plain OFDMA for increasingly similar SNRs.

4 Feedback detail

4.1 Codebook size

In order to provide CSI feedback, we measure it using pilot symbols, quantize it and send it back to the transmitters. Similarly to state-of-the-art systems such as LTE, we use a codebook approach. The codebook is known at both MSs as well as APs and contains quantized CSI values. Hence, MSs do not need to send back full CSI values, but only the index of the codebook value which is most similar. The larger the codebook, the more similar values can be found, but also the larger is the index in terms of bits, which directly affects overhead. Hence, finding a suitable codebook size is key for IA to work correctly.

In order to find such an appropriate codebook size, we use an experimental approach. We estimate channels in a software-defined radio (SDR) testbed, quantize them with different codebook sizes, use them for IA and measure the resulting bit error rate (BER). We test codebooks sizes ranging from 2 to 4096 entries and M-QAM modulation orders from $M = 4$ to 256. The results are depicted in Figure 3. As expected, the BER becomes smaller for larger codebook sizes, since more precise CSI is available at the transmitter. Also, the higher the modulation order, the larger the BER, since errors are more likely in dense constellations. We observe that for all modulation schemes the BERs stabilize at a codebook size of about 64 entries. While a smaller codebook size is not precise enough for IA and causes errors, a larger codebook is pointless as it does not improve performance but increases feedback overhead. Thus, we conclude that 64 is a suitable codebook size for our testbed.

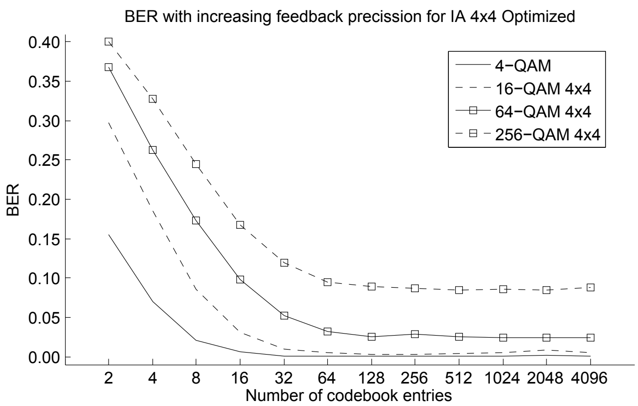

Figure 3: BER with increasing feedback precision for IA.

4.2 Overhead impact in indoor environments

The impact of overhead is not only influenced by the size of the codebook, but also by how often feedback needs to be sent to the transmitters. This in turn is directly related to the coherence time of the channel, since each time the channel changes, CSI needs to be measured. In the following, we determine the coherence time for typical indoor environments, which is our scenario in this report. Specifically, we consider that channels change at the rate imposed by human speed, which is about 5 km/h. This translates into a maximum Doppler spread of $f_{D,max} = \frac{f_C \cdot v_{max}}{c_l} = 11.04$ Hz, where f_C is the center frequency and c_l is the speed of light. Hence, the coherence time is approximately $t_{coherence} = \frac{1}{2 \cdot f_{D,max}} = 45.28$ ms.

5 Feedback robustness

CSI is sent back to the transmitters via a wireless feedback channel which itself might cause transmission errors and thus deliver wrong CSI to the transmitters, which in turn will calculate wrong precoding vectors. To assess the impact of wrong CSI on the IA frame, we first study by simulation how the IA BER increases the more random bit errors we intentionally add to the CSI feedback, which is protected by a rate 1/2 convolutional code. We then measure in practice the average BER of an OFDM feedback frame in a SDR testbed setup and compare it to our simulative results to find out its impact on IA. The result is shown in Figure 4. We observe that bit errors on the feedback frame for BER $\leq$ BER$_{ths} = 10^{-2}$ do not affect the IA transmission at all, since curves are virtually stable up to that value. However, beyond that threshold IA performance degrades as there are too many errors in the feedback frame. The continuous vertical line in Figure 4 represents the average OFDM BER in our testbed, which is about $8 \cdot 10^{-6}$ and thus not critical for the CSI feedback.

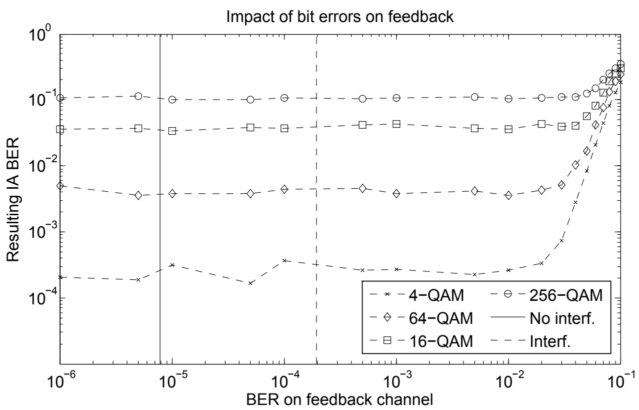

Figure 4: Impact of bit errors on feedback for IA in the frequency domain.

However, in practice the CSI feedback transmission might also be affected by external interference not present in our lab environment. Hence, we include an interferer in our practical setup and measure the OFDM BER when adding artificial noise. We set the transmit gains of the interferer to suitable values in order to avoid fully jamming the channel but still generate moderate interference. The result is represented by the dashed vertical line at $2 \cdot 10^{-4} \leq$ BER$_{ths}$ in Figure 4. Since the BER we measure is less than the threshold above which the errors on feedback affect the IA transmission, we conclude that feedback is also robust in the case of interference.

6 Conclusions

In this report we study the impact of three real-world effects on Interference Alignment (IA) in the frequency domain for the downlink in a wireless access network. In particular, we have analyzed the impact of heterogeneous SNRs on IA, the level of detail required for CSI feedback, and the robustness of the Channel State Information (CSI) feedback which is required for IA. By means of simulation, we observe that IA works better when each involved node has similar and high SNRs to each access point (AP). In our SDR testbed, a codebook size of 64 proves to be a good trade-off between CSI precision and overhead. Regarding feedback robustness, we find that a plain OFDM transmission protected with a 1/2 convolutional code can reliably deliver CSI to the transmitters in order to perform IA, also in the case of moderate interference.

References

[1] V. R. Cadambe and S. A. Jafar. Interference alignment and degrees of freedom of the k-user interference channel. *IEEE Trans. on Information Theory*, 54(8), 2008.