ECEN 410 - Adv. Communications Engineering Project 1: Distributed MIMO

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***Abstract*—Distributed MIMO (Multiple-Input-Multiple-Output) has been analysed here with respect to multi-user use for the uplink case. We observe the asymptotic effects of increasing transmission power due to interference by neighbouring cells. These effects are more pronounced for where distributed antennas are closer to the cell edge. However, this is less pronounced that the reduction of distance between the antennas and the users in the cells, generally increasing ergodic achievable rates.**

I. Introduction

The onset of 5G cellular standards and large antenna arrays (Massive Multiple-Input-Multiple-Output (MIMO)) have introduced a new question with respect to how base station antennas are distributed. This is as geographically distinct antennas may allow for the benefit of spatial diversity. This may be exploited for multiple users [1] and for the multiple distributed base station antennas [2]. This report explores a representative model of MIMO cells to obtain an idea of how potential distributive base stations may increase the overall throughput of a channel.

II. Modelling Concerns

To develop a representative perspective of the channel model, we must consider what general operating mode we will model and consider. Primarily, we want to see how multi-user use of the channel may be affected by this interference.

A. Multi-user MIMO

A major aspect of MIMO that may be exploited in future standards is that multiple users may be served by a base station in the same allocated resource block [1]. The general concept is that the more unique each of the user's environments are, the more distinguishable their respective data streams are. Therefore, the streams may be separated with linear encoding and decoding schemes in the same environment. MIMO allows for multiple streams of data to be present at the same time so it may be possible to decode these [3].

For the analysis in this project, the users will each have one antenna each while the base station has multiple antennas. This simplifies the analysis while providing indicative information of how total channel performance works.

B. Antenna Distribution

With multiple users there may be a variety of different distances for each of them from each of the base station antennas. This means that if the base station antennas are located at one point, there will be some users that will be further away so their dedicated data stream would be poorer. However, if the base station antennas were distributed around the cell, each user would have on average a smaller distance between a base station antenna. Therefore, the multiple usable data streams becomes viable once again.

Distributed antennas may lead to generally less distance and loss to its users in exchange for stronger interference form neighbouring cells. The closer positioning with neighbouring cells introduces the issue of interference. Unwanted powerful signals contaminate and reduce the signal to interference and noise ratio (SINR). This implies asymptotic performance for an increased signal power for the cells as increased power corresponds to increased interference.

For the analysis that will be made, each antenna will be distributed uniformly angle wise around the cell centre and at a fixed radius as similar considered by [4]. This minimises the potential distance between the user cells. The directly neighbouring cells will also share the same antenna distributions and the same number of served users. No neighbours beyond will be modelled as they are assumed to be negligible.

C. Wireless Channel Model

Distributed and multi-user MIMO deal with the following aspects for each link between a user and a base station antenna: fading, shadowing, and path loss.

A channel is described by the matrix $\mathbf{G} \in \mathcal{C}^{M \times K}$, where M is the number of base station antennas, and K is the number of users sharing a resource block in the cell. Each column $\mathbf{g}_k$ describes the channel between each user k and the base station antennas. This is expressed as:

$$\mathbf{g}_k = \sqrt{\beta_k}\mathbf{h}_k \tag{1}$$

The small-scale fading term will be described with a unit Rayleigh distribution:

$$\mathbf{h}_k \sim \mathcal{CN}(0, 1) \tag{2}$$

This assumes that there will be no line of sight and rich scattering for the receiver. This is a limited assumption as base station antenna typically are set high to attain a line of sight [5].

$\beta_{k,m}$ describes the received power at the m^{th} antenna from the k^{th} user. This is determined as:

$$\beta_{k,m} = d_{k,m}^{-\gamma} L \tag{3}$$

where $d_{k,m}$ is the distance between the user and the base station antenna, $L \sim \log\mathcal{N}(0, \sigma_{sf})$ is shadowing due to obstructions, and γ is the path loss. The received power in this term is considered constant for each transmission, i.e the system is coherent for each transmission.

We will consider the *uplink transmission* for the analysis. This means that the users are transmitting at a fixed power and the base station antennas are receiving the user's data. This allows for a more tractable analysis of how the many user power sources affect their antenna destinations.

D. Coding Scheme and Interference

Elimination of interference of error in a cell will use the linear coding scheme zero forcing combining [6]. This requires that the base station has knowledge of the channel $\mathbf{G}$ to diagonalise the channel. This linear coding scheme takes the pseudo-inverse of $\mathbf{G}$ and applies it to the received symbols at the receiver, i.e. where

$$\mathbf{y} = \sqrt{p}\mathbf{G}\mathbf{x} + \mathbf{n}, \tag{4}$$

then

$$\begin{aligned} \mathbf{r} &= \mathbf{G}^{\dagger}\mathbf{y} && (5)\\ &= \mathbf{G}^{\dagger}\mathbf{G}\mathbf{x} + \mathbf{G}^{\dagger}\mathbf{n} && (6)\\ &= \sqrt{p}\mathbf{x} + \mathbf{G}^{\dagger}\mathbf{n} && (7) \end{aligned}$$

Note that we assume that this coding may only deal with the users in the cell and not for neighbouring cells. The resulting SINR for each user with *no* inter-cell interference is:

$$\text{SINR}_k = \frac{p\sum_{m=1}^{M}\beta_{k,m}}{\sigma^2[(\mathbf{H}^H\mathbf{H})^{-1}]_{k,k}} \tag{8}$$

When we consider the inter-cell interference where users outside of the cell are also transmitting, we obtain the term:

$$\text{SINR}_k = \frac{p\sum_{m=1}^{M}\beta_{k,m}}{\sigma^2[(\mathbf{H}^H\mathbf{H})^{-1}]_{k,k} + \text{I}} \tag{9}$$

where,

$$\text{I} = p\sum_{m=1}^{M}[\mathbf{H}^{\dagger}]_{m,k}\sum_{k'=1}^{K'}\beta_{k',m}h_{k',m} \tag{10}$$

In these terms, k' is the index of each interfering user and K' is the total number of interfering users. Hence, $\beta_{k',m}$ is the received power at the base station antenna from the interfering user, $h_{k',m}$ is the Rayleigh fading, and $[\mathbf{H}^{\dagger}]_{m,k}$ is the zero forcing combining applied to the interfering signal.

The SINR for each user given in (9) for uplink performance exemplifies the complexity of accounting for unwanted users for a cell's performance.

E. Spectral Efficiency

Now that we have obtained an expression for the SINR for each user's uplink in the cell, we must now evaluate the general performance over the entire cell. The data stream uplink spectral efficiency, the maximum achievable rate given some processing for a user, is given by the expression [7]:

$$R_k = \log(1 + \text{SINR}_k) \tag{11}$$

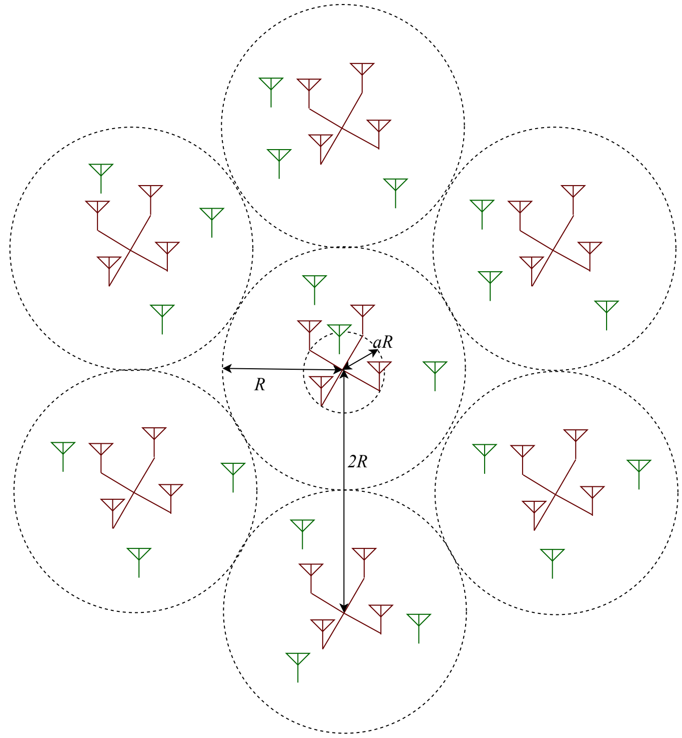

Fig. 1: Multi-user distributed MIMO setup of uplink connectionz for $K = 3$ users and $M = 4$ base station antennas. The green antennas are the single transmit antenna users for each of the cells. The red antennas are the base station receiving antennas for each of the cells. We focus analysis on the center cell.

To obtain general performance, we acquire the ergodic sum spectral efficiency with:

$$\mathbb{E}[R_{\text{sum}}] = \mathbb{E}\left[\sum_{k=1}^{K} R_k\right] \tag{12}$$

We will calculate this for different transmit powers, p, so that we may see how ergodic performance changes for different user transmit powers.

III. Simulation Methodology

The simulation of the channel performance for uplink spectral efficiency requires that the interfering cells and the primary cell are both modelled appropriately. Figure 1 illustrates the setup for each of the users and antennas. The variables of the user and antenna distributions are as follows:

- R is the radius of the cell where users are dropped within.
- a is the distance of the base station antenna from the cell center. $a \in [0, 1]$ so that it may be within or on the edge of the cell.
- K is the number of users in each cell in each resource block. We assume that the uplink session is synchronised with all neighbouring cells, i.e. there are no antennas transmitting in the simulation.
- M is the number of antennas on the base station of each cell.
- $\text{user}_{\text{pos}} = de^{j\theta}$ where $d \sim \mathcal{U}[0, R]$ and $\theta \sim \mathcal{U}[0, 2\pi)$.

Simulation Variable	Value
Cell Radius, R	1km
Neighbouring Cell Count	6
Path Loss, γ	4.6
Shadowing Standard Deviation, σ_{sf}	10
Base Station Antennas, M	4
Users per cell, K	6
Ambient Temperate, T	290°K
Noise Bandwidth, B	5MHz

TABLE I: Wireless channel variables for the simulations. Any deviations from these will be explicitly stated.

- antenna$_{\text{pos}} = aRe^{j\theta}$ where $\theta \sim \mathcal{U}[0, 2\pi)$

The following assumptions on the receiving base antennas will be made:

- the receiving antennas will be subject to independent Rayleigh fading,
- for the non-distributed case, $a = 0$, the shadowing for all of the antennas for each user will be assumed to be the same for each simulation. This assumes that the entire antenna array encounters the same extent of shadowing for the transmission period.
- correspondingly, the distributed antennas simulation will have independent shadowing as they are all assumed to be far enough that they have independent shadowing between them.
- the distributed receiving antennas are assumed to be connected with no delay, infinite bandwidth fibre. As in, decoding is assumed to be equivalent to the non-distributed case.

Table I details each of the variables and their values used for the simulations. The simulation variables correspond to a simplified 2 dimensional radio propagation model of non-line-of-sight (NLOS) 28 GHz transmission [8].

IV. Results and Analysis

A. Effects of Inter-cell Interference

There is a trade off between how far the antennas are from the cell centre in terms of the power of the transmitting cell users and transmitting interfering users. We analyse the positive effect of the former in Figure 2 where there is no inter-cell interference. We generally see that distributed antennas out perform the non-distributed case. This would be due to the average user being closer to a base station antenna, hence there is far less of the most dominant loss in radio propagation – path loss.

The $a = \frac{2}{3}$ distribution in this example outperforms the others. Out of the a values tested, this generally minimises the distance of a uniformly distributed user from a distributed antenna. We see that moving the antennas to the cell edge with $a = 1$ causes a reduction in performance as now the antenna are generally further away from the cell users. Far more of their range would be over the neighbouring cells.

Finally, the non-distributed cell does not take advantage of increased diversity of independent shadowing, causing a reduction in performance.

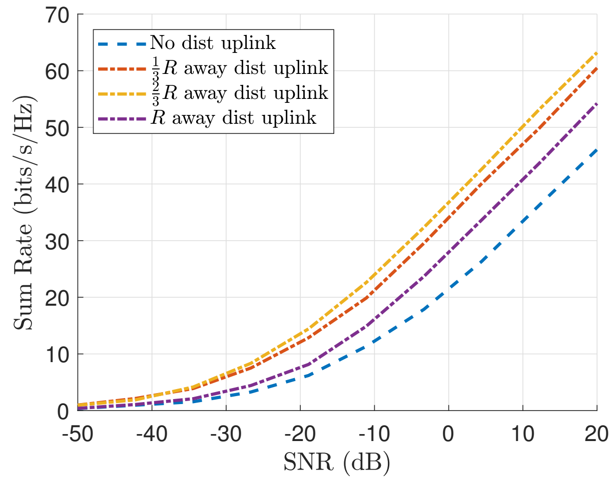

Fig. 2: Comparison of different antenna distributions' sum rate for where there is no inter-cell interference. The SNR on the horizontal axis is the transmit SNR that is uniform for all users in the cell.

When we consider inter-cell interference as shown in Figure 3, we see an adverse effect by the transmitting users on the sum rate. There is asymptotic behaviour as the transmit power by each user uniformly increases. There is a significant penalty for antennas placed further from the centre as they are subject to more transmission interference by the neighbouring cells. This is especially exemplified by the antennas being placed on the cell edge (R away dist). The receiving antennas are directly competing with the interfering users and their uplink transmissions.

The non-distributed MIMO becomes more viable for this case and the former leader of $a = \frac{2}{3}$ is beaten by the $a = \frac{1}{3}$ variant. This indicates that the gains of movement away from the centre need to be balanced by the losses by being too close to the edge. In addition, we may observe that the asymptotic trend begins to become apparent for transmit SNRs above -10dB.

The asymptotic behaviour from increasing only SNR become apparent for Figure 4 where we see that the different distributions become far more comparable when interference is taken into account. For example, a transmit SNR of 20dB has the performance gap between the no antenna distribution and $a = \frac{2}{3}$ antenna distribution drop from 17 bits/s/Hz to 1 bits/s/Hz. This reduces the distributive technique's viability significantly.

B. Users Per Cell

When we alter the number of users in each cell, we see that generally the sum rate of the primary cell is positively correlated (shown in Figure 5). However, they all taper off to give each individual user a lower average sum rate. The $a = \frac{1}{3}$ distribution outperforms or performs at par the other distribution techniques for multi-user MIMO ($K > 1$).

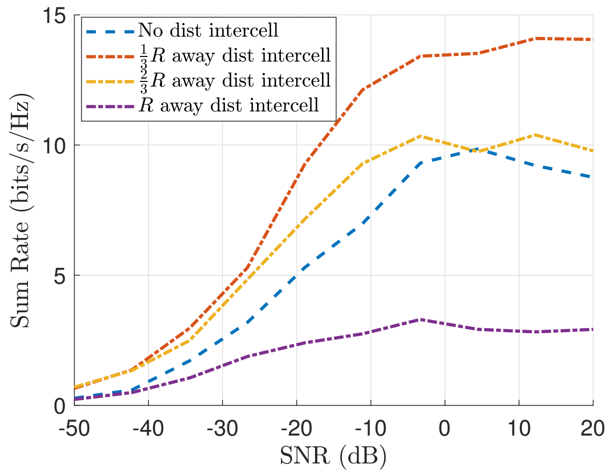

Fig. 3: Comparison of different antenna distributions' sum rate for where inter-cell interference is present. The SNR on the horizontal axis is the transmit SNR that is uniform for all users in all cells.

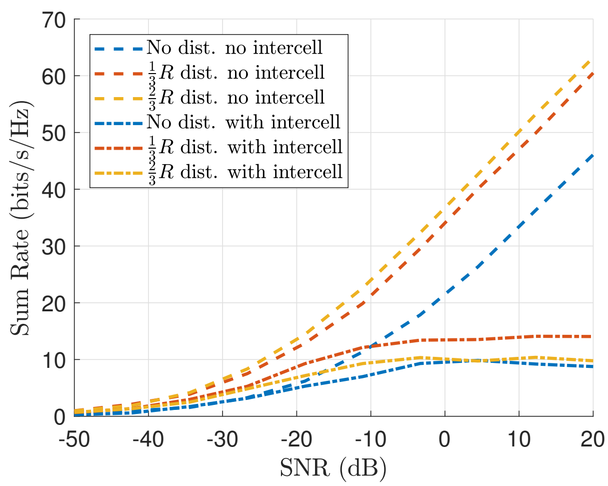

Fig. 4: Comparison between the different antenna distributions' sum rate with respect to the presence or absence of inter-cell interference. The SNR on the horizontal axis is the transmit SNR that is uniform for all users in all cells.

V. Conclusion

We have observed in this report that distributed MIMO may generally outperform non-distributed MIMO as long as a balance is made between the interference experienced at the cell edge and the distance from users at the cell centre. Inter-cell interference introduces asymptotic behaviour for increasing transmitter uplink power, indicating the gains made with antenna distribution pushes the limit further. The trade-off between the expense of implementing distributed MIMO versus the limiting factor of interference is strongly present however.

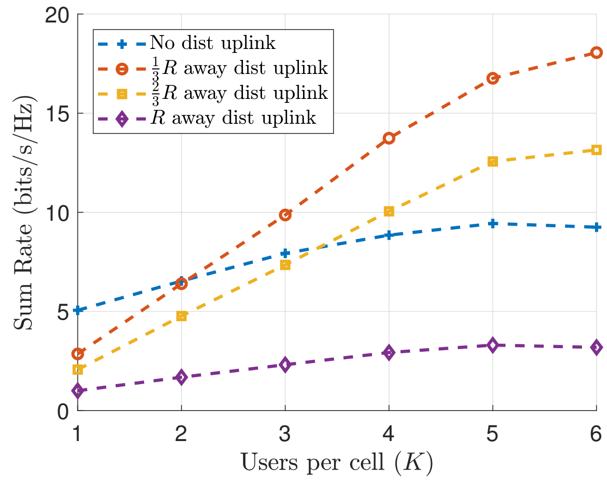

Fig. 5: Sum rates for different amounts of users in each cell for each proposed distribution of base station antennas. M = 4 bases station antennas, transmit SNR = 20dB.

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