List of Abbreviations

BLER	Block Error Rate
CQI	Channel Quality Indicator
CSI	Channel State Information
FNBW	First Null Beam Width
GoB	Grid of Beams
MCS	Modulation and Coding Scheme
MRT	Maximum Ratio Trasmission
OLLA	Outer Loop Link Adaptation
PRB	Physical Resource Block
SINR	Signal-to-Interference-plus-Noise Ratio
TB	Transport Block
TTI	Transmission Time Interval
UE	User Equipment
ZF	Zero Forcing

List of Symbols

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Modelling

Contents

1.1 Grid of Beams

To create a GoBs, the directions to which to steer the beam need to be known. The beam-steering directions are all possible combinations of values in the azimuthal and elevation angular domains. And to create one of such domains, one simple way is to use the resolution and the values of the extremes. Defining in Equation (1.1) an interpolation function to perform the operation of creating a set of values from a to b, given b strictly greater than a, with intervals of resolution r.

$$F_I(a,b,r) = \left\{ a + i \times r, \forall\, i \in \mathbb{N}_0 : i \times r \leq \frac{b-a}{n} \right\} \tag{1.1}$$

This way, one defines the azimuthal angular domain as $\mathcal{A}_\varphi = F_I(a_\varphi, b_\varphi, r_\varphi)$ and the elevation angular domain as $\mathcal{A}_\theta = F_I(a_\theta, b_\theta, r_\theta)$. If the antenna is positioned in the centre of the room, a symmetric approach is the most logical. The GoB should cover all possible positions of the UEs, hence given the position and movement of the users in relation to the size of the room (see Section **??**), we've set the lower limits to $a_\varphi = a_\theta = -60$° and the upper limits to $b_\varphi = b_\theta = 60$°.

The resolutions should depend on the array size. To create a pseudo-non-interfering GoB, where the maximum of the main lobe of one beam points at the a minimum of an adjacent beam, the resolution should be roughly half the First Null Beam Width (FNBW). It was called 'pseudo-non-interfering' because the FNBW varies with the direction at which the beam is steered, therefore this method is a simplistic yet effective approach to minimising the interference between beams.

To conclude, the possible directions can be defined as a cartesian product between the azimuthal and elevation domains, as shown in Equation (1.2)

$$\mathcal{D} = \mathcal{A}_\varphi \times \mathcal{A}_\theta = \{(\varphi, \theta) :\ \varphi \in \mathcal{A}_\varphi,\ \theta \in \mathcal{A}_\theta\} \tag{1.2}$$

P are the beam-steering vectors, or precoders.

$p_{a,e}$ is a beam-steering vectors computed to maximise the power in direction a, e, e.g. $p_{30,45}$

1.2 System-level Simulator

In this section, we detail the functions executed and information collected during a system-level simulation.

The system-level simulation consists of three main steps: first, the generation of application traffic in accordance with the application layer parameters (defined in Section **??**); second, the initialisation of all variables that are required for the simulation or that will be stored during the simulation - such variables may at any time be expanded to include a less apparent metrics; and third, the simulation itself, where each Transmission Time Interval (TTI) is separately processed

The main steps conducted during system-level simulation of TTIs are:

1. Update Channel State Information (CSI)
2. Update Scheduling
3. Process Transmissions

1.2.1 Update CSI

We access the TTI regarding the CSI update triggering property consists of a checking if the modulo with the CSI periodicity parameter is null. Only in case the previous TTI is a CSI-collection TTI the steps below take place.

1. Update best beam-pairs for each polarisation of each UE, for each BS - given a UE and BS pair, firstly, the best beam-pairs between them are computed. The best beam-pairs are are defined based on the gain achieved from using a given TX precoder and a RX precoder (combiner) over a channel that connects the TX and RX polarisations. The precoder on the BS side is always a beam steering precoder from the GoB, that may be tapered (i.e. weights with different amplitudes across antenna elements) or not. And the UE-side precoder is always the Maximum Ratio derivation that fits the use of BS precoder and the channel. More generally, the BS precoder of choice is given by Equation (1.3), and the UE precoder is given by the MRT/MRC (respectively, in UL/DL) correspondent computation, in Equation 1.4.

$$p_{BS} = \underset{p \,\in\, \mathcal{P}}{\operatorname{argmax}} \left(c_{bm} \cdot \frac{p}{|p|} \right) \tag{1.3}$$

$$p_{UE} \tag{1.4}$$

Note that $\mathcal{P}_b$ was defined in Section **??** as the set of precoders in BS b Grid of Beams (GoB), and c_{bm} is the The beam-pair computed will be used for UL and DL transmissions. The best beam-pair determines the polarisations

continue

2. Update the interference measurements for each polarisation of each UE or BS, respectively, in case of DL or UL - to use the non-zero experienced interference from $\text{TTI}_{\text{delay}}$ TTIs ago. If the interference of said TTI is null, then the next most recent non-zero interference measurement is used instead.

Regarding the precoders' update step, note that using the same beam-pair in UL and DL is not optimal in some situations. Assume DL transmission and that one polarisation in the BS is best received by one UE in both polarisations. In this case, the optimal situation would be to transmit both layers with that polarisation in the BS and receive each layer in each of the UE polarisations. Yet, this cannot happen if the same beam-pair is subsequently used for the UL because the reception of different layers with the same polarisation in the BS would lead to very intense interference. Therefore, if the beam-pairs are direction-specific, we are able to cover also such edge cases. Also here we see work for the future.

With regards to the interference update step, a major disadvantage of estimating the interference in this manner comes from the fact that the experienced interference is extremely dependent on which UEs are scheduled, and what the beams used, in that given TTI. If the scheduled UEs or precoders in use change, then there a major change in the experienced interference takes place. We foresee precise interference estimation algorithms, perhaps driven by learning mechanisms, to be a future direction of work. For future work related discussions, see Section **??**.

Despite the drawbacks of the last two paragraphs, the CSI modelling is coherent and realistic.

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1.2.2 Update Scheduling

Analogous to the 'Update CSI' procedure, the 'Update Scheduling' phase is only executed in the respective TTIs, depending on the scheduling periodicity. The refresh of which UEs to schedule with

1. List UEs to consider for scheduling - the ones with non-empty buffers are examined to make part of the list of scheduled UEs. It wouldn't make sense to schedule a UE with nothing to send/receive (respectively, when updating the UL or DL schedule);

2. Select BS per polarisation one the UE - the BS with the best beam-pair for a given polarisation in the UE is considered as the serving BS for that polarisation;

3. Select SU-MIMO setting on the number of layers - either a single layer or a dual-layer setting is selected. The setting that gives highest aggregated bitrate

is chosen. If only one layer is transmitted, it can be transmitted with double the power used per layer in a dual-layer transmission, since it uses the power assigned to the unused layer as well. The selected polarisation for a single-layer transmission is the one that has the highest SINR and the receiving polarisation that pairs best is selected. In the dual-layer transmission there will be a bitrate per data stream. The reception is done with the respective polarisations that maximise each layer's SINR, provided the polarisations are different.

To estimate the bitrate, the procedure is the following:

   (a) Use the SINR to estimate the MCS from the Modulation and Coding Scheme (MCS) curves - pick the first Channel Quality Indicator (CQI) that achieves a lower percentage of block errors than the Block Error Rate (BLER) target (set to 10 %).

   (b) (Optional) Adjusts the MCS choice with the Outer Loop Link Adaptation (OLLA) parameter. It can be UE specific or global. detail the OLLA para

   (c) From the selected MCS and the assigned resources, estimate the achievable bitrate.

4. Compute priorities based on the estimated instantaneous bitrate. Depending on the scheduler, it may consider the latencies as well.

5. Select MU-MIMO setting: list the users that will be co-scheduled. The co-scheduling rule is to add the layer or layers of a UE to the list, by order of User Equipment (UE) priority, if the best beams used for those layers are compatible with the previously added UE layers. We define as incompatible layers with beam-pairs from the GoB that are at less than k beams apart. If k is 0, then the all layers are accepted. If $k = 1$, then the beams must be different - adjacent beams have a distance of 1. Beams located diagonally adjacent of the GoB are considered to have a distance of 2, hence they may be co-schedule with $k = 1$ and $k = 2$. Beam distance is defined by the sum of differences of the beam indices in the grid. Also, incompatibility is only checked with layers from different users as the SU-MIMO choice before should have decided one the same user layers. add example based o previous GoB formula

6. Distribute the maximum total transmit power amongst the scheduled UEs.

7. Re-estimate the SINRs, per UE, per layer, based on:

   (a) the number of layers each user will actually have, if it has changed from the last estimation

   (b) the newly assigned power

8. Choose the final MCS, per UE, per layer, based on the last SINR estimate

There are three noteworthy remarks about the above:

- It can be performed on a narrowband level: we may do the above for portions of the band. The only thing that needs to change across the schedulable bands is the aggregated-across-time throughput metric in the scheduler, or else the resources would be attributed equality anyway. Therefore, instead of the actual aggregated-across-time throughput, we should use and estimated aggregated-across-time throughput, and update that estimation with the expected bitrate each user would get from the schedulable narrowband. For the first portion of band, the estimation and the actual values would be the same. Note that if the scheduler takes into account latencies as well, then the head-of-queue delay value provided to the scheduler must change across narrowbands, it should assume the bits are correctly sent and compute the latency of 'the next packet on the queue'. Or something even smarter, perhaps like considering a few more packets ahead of time, since it will take a while until the scheduling changes.
- It can be performed for UL as well, with small changes:
  - The PRBs attributed should depend on the channel quality of the UE, and a Power Density should be computed to achieve a certain SINR per PRB.

    per and input com-
    lues

  - The interference needs to be computed differently for the uplink. Same principle, but different variables since other UEs are causing the interference. Furthermore, the wideband interference estimates can be adjusted to equate the total interference in the UL band;
  - The noise needs to be computed differently since we won't know how big the bandwidth will be ahead of time. For the first estimation, it is enough to consider the same bandwidth for all users, or to estimate based on the quality of the beam-pair (channel gain measured when CSI measure was obtained). Then, when the actual priorities are defined, a new and more precise value can be used for the noise. Moreover, since interference is expected to me far more relevant than noise, the wideband noise can be considered for both cases, giving a marginally different estimate, even though it is a worst case scenario estimate noise-wise.
  - The transmit power in the UL is always the same, it may be more or less distributed across frequency. Unless the in SINR is limited by too much interference and using the less power results in similar SINRs, which is rarely the case, the transmit power can be always maximum.

- It can be performed for Implicit beamforming, with small changes:
  - The first SINR estimation is performed with Maximum Ratio Trasmission (MRT) precoders;
  - The second SINR estimation is performed with Zero Forcing (ZF) precoders - that computation requires the MU-MIMO setting;
  - Anything else?!
- When more BSs are used, and when more beams besides the best are reported, something more intelligent can be made in the BS selection. Nonetheless, it is assumed that all BSs communicate at a very fine time scale between them, to choose how to best serve the UEs.

Steps on Simulating the TTI:

1. Get the Transport Block (TB) size from the MCS used and the allocated number of PRBs. There's a TB per bandwidth part.
2. Compute the realised SINR, for each scheduled UE:
   (a) Compute Intra-cell interference
   (b) Use default value of Inter-cell interference.
   (c) Compute Noise.
   (d) Compute RSS.
3. Compute BLER.
4. Flip a BLER-biased coin to determine if the block was well received or had errors
5. (In case OLLA is used) Update the OLLA parameter based on success or not from the block transmission.
6. Update the time-aggregated throughput per UE

Bibliography