List of Abbreviations

BLER	Block Error Rate
BS	Base Station
CQI	Channel Quality Indicator
CSI	Channel State Information
EXP/PF	Exponential/Proportional Fair
GoB	Grid of Beams
MCS	Modulation and Coding Scheme
MIESM	Mutual Information Effective SINR Mapping
M-LWDF	Maximum-Largest Weighted Delay First
OLLA	Outer Loop Link Adaptation
PRB	Physical Resource Block
RE	Resource Element
SINR	Signal-to-Interference-plus-Noise Ratio
TB	Transport Block
TBS	Transport Block Size
TTI	Transmission Time Interval
UE	User Equipment

List of Symbols

Δ_{OLLA}	outer loop link adaptation step
N_r	number of receiving antennas
N_t	number of transmitting antennas
$N_{\text{CSI Beams}}$	number of beams with CSI-RS, per polarisation
N_{BS}	number of Base Stations (BSs)
N_{UE}	number of User Equipments (UEs)
M	modulation order
$N_{\text{symb}}^{\text{PRB}}$	number of symbols per PRB
$N_{\text{bits}}^{\text{symb}}$	number of bits per symbol
$N_{\text{info bits}}^{\text{symb}}$	number of information bits per symbol
$N_{\text{bits}}^{\text{slot}}$	number of bits per slot
R_{B}	bit rate
$BLER_0$	target Block Error Rate (BLER)
γ_{OLLA}	step size for OLLA parameter (Δ_{OLLA}) update
$\boldsymbol{w}$	beamforming vector of weights
$\boldsymbol{H}_{bmp}$	channel matrix between BS b and UE m in BSs polarisation p
$p_{\phi,\theta}$	beamformer part of a GoB with direction (ϕ, θ)
$p_{i,j}$	beamformer part of a GoB with grid indices (i, j)
τ_{tti}	TTI delay
T_{sch}	period for updating scheduling information
T_{csi}	period for updating Channel State Information (CSI)
$\lvert \cdot \rvert$	euclidean norm of vector
$\boldsymbol{A}^{\text{H}}$	hermitian of $\boldsymbol{A}$, also know as the transpose conjugate of $\boldsymbol{A}$
$\lceil a \rceil$	ceil a, i.e. round a to the next integer
$\lfloor \cdot \rfloor$	floor a, i.e. round a to the current integer (discards decimal part)

1

Modelling

Contents

1.1 System-level Simulator

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In this section, we detail the functions executed by the network equipment during a simulation. The network equipment receives the radio channel coefficients across time from the channel generator and the application requirements in a form of packets to arrive in certain Transmission Time Intervals (TTIs). The BS has to handle important tasks such as the update of the Channel State Information and the numerous procedures related with individually processing the transmission of each TTI, in order to imitate the radio connection present in a XR Conference.

See Figure

flowchart with steps of SLS

Firstly, at the very start of the TTI, it is identified as a DL or UL TTI. This implies a hard TDD split, in the sense that there aren't flexible slots where either UL or DL transmission is allowed. What is a good TDD split and what is a good frame size? The TDD split should match the throughput requirements, i.e. if the aggregated information to send in the downlink totals twice the information to send in the uplink, then a 2:1 TDD split should offer the best results, from this *à priori* analysis. Regarding the frame size, mind the structure defined by 3GPP, where first all DL slots are . On one hand, the frame size can't be too extensive, or some UEs may starve of throughput and expire the packet latency budgets, leading to excessive packet drops. On the other hand, the frame size must be big enough to support the TDD split defined above. Given the application specifics defined the **??** referring to how the total UL load is proportional to the number of physically present users and DL load changes proportionally to the number of participants, including remote participants too, the TDD split should be chosen in conformity with the scenario specifics.

Before processing the actual TTI, it is verified if CSI should be updated, given the chosen CSI periodicity T_{csi}. Then, it is also checked if the current scheduling information for that TTI is to be updated. Only after those two procedures is the present TTI processed. Firstly, how CSI is updated and how the scheduling decisions are made.

1.1.1 Update CSI

Only in case the previous TTI is a CSI-collection TTI there is an update on the best beam pairs between the UE and the BS(s), determining the best directions for transmission, and refreshing the interference measurements.

To update the best beam pairs between UE and BS, several details must be laid down. Firstly, we consider that each BS transmits each polarisation separately. This assumption derives from the fact that at least two independent streams/layers must be supported per UE, and the only way of not sacrificing performance while guaranteeing orthogonality in polarisation domain. Hence, the BS sends CSI-RSs coded into $N_{\text{CSI Beams}}$ beams, per polarisation. 3GPP defines up to four of the beams received the best can be fed back to the BS. We are stepping into manufacturer's implementation domain perhaps, but we assume at most four per polarisation.

Thus, in essence, each BS sends schedules CSI resources on each UE and sends at most four CSI-RS per polarisation, coded in different beams. However, to facilitate beam choice, we make decisions based only on the best beam reported per BS, per polarisation. See Section **??** on how other possible choices.

The best beam-pair, per BS polarisation is chosen by maximising the channel gain achieved from performing a transmission with a given GoB beam, over the channel of that polarisation, and doing best effort at the reception to received that signal, using Maximum Ratio Combining (MRC). MRC, as shown in Equation (**??**), leads to a purely real signal with amplitude equal to the square of the norm of the incoming signal. As such, when maximising the norm of the received signal in cases where the received beamformer is a MRC it we only have control to choose the appropriate GoBs beam to use. Provided that all beamformers, by definition, are normalised (making the total radiated/received power not changing), the internal product of a precoder p belonging to the set of beamformers in BS b Grid of Beams (GoB) $\mathcal{P}_b$ (defined in Section **??**) with the channel coefficients h_{bml} is sufficient to obtain the norm of the signal arriving to each of the UEs antennas. Equation (1.1) summarises the choice of precoder for the BS for a case where $N_{\text{CSI Beams}} = 1$.

$$\boldsymbol{w}_{\text{BS}} = \underset{\boldsymbol{w}\,\in\,\mathcal{W}_{\text{GoB}}}{\operatorname{argmax}} \left(\boldsymbol{w}^{\mathsf{T}} \cdot \boldsymbol{h}_{bml} \cdot \boldsymbol{w}_{\text{UE}}^{\text{MR}}\right) = \underset{\boldsymbol{w}\,\in\,\mathcal{W}_{\text{GoB}}}{\operatorname{argmax}} \left(\boldsymbol{w}^{\mathsf{T}} \cdot \boldsymbol{h}_{bml}\right) \tag{1.1}$$

An analogous procedure is done to discover the $N_{\text{CSI Beams}}$ best beams.

The beamformer on the BS side is always a beam steering vector from the GoB, and the UE-side precoder is always the Maximum Ratio beamformer that fits perfectly the use of the BS beamformer and the channel. The UE precoder is given by the MRT/MRC (respectively, in UL/DL) correspondent computation, in Equation 1.2.

$$\boldsymbol{w}_{UE} = \frac{\left(\boldsymbol{h}_{bml} \cdot \boldsymbol{w}\right)^{H}}{\left|\boldsymbol{h}_{bml} \cdot \boldsymbol{w}\right|} \tag{1.2}$$

The beam-pair computed in this way is used for UL and DL transmissions exploiting TDD reciprocity.

The result from the update is a list of the best $N_{\text{CSI Beams}}$ between each UE and each BS, per BS polarisation.

It is relevant to talk about how multi-layer transmission is modelled. In the DL, not all antenna elements are used for each transmission. Only half of the elements transmits in each polarisation, the half that has the correspondent orientation. Provided that the power radiated per layer is not changed by different numbers of elements for the transmission, then to consider half the antenna elements it is not problematic. In the UL, the BS can receive using both polarisations for the reception. In doing so, it combines element contributions by using the same precoder in each polarisation and adding up the signals.

Furthermore, in this work we consider a maximum of two independent layers per UE, and that those layers can must be sent by the same BS. Although that is a limits the flexibility and the purpose of multi-BS simulations, it has to be left as future work (see Section **??**).

Regarding the interference measurements update, it is used the interference from τ_{TTI} TTIs ago. A major disadvantage of estimating the interference in this manner comes from the fact that the experienced interference is extremely on which UEs are scheduled and what beams are used in that given TTI. If the scheduled UEs or beamformers in use change, then is expected a major change in the experienced interference to take place. We foresee precise interference estimation algorithms, perhaps driven by learning mechanisms, to be a future direction of work. We discuss this matter further in Section **??**.

Despite this last inevitable drawback, the modelling of CSI acquisition and feedback is coherent and realistic.

1.1.2 Update Scheduling

Analogous to the 'Update CSI' procedure, the 'Update Scheduling' phase is only executed in the respective TTIs, depending on the scheduling periodicity. Some authors consider updating the scheduling information every two TTIs [1], to match LTE. Other authors [2] prefer updating as frequently as possible. We defined a parameter called the scheduling periodicity T_{sch} (in TTIs), to be tuned.

what else needs to be explained ahead of time?

The scheduling procedure is described by the following steps:

1. List UEs to consider for scheduling - UEs with non-empty buffers are examined to make part of the list of scheduled UEs.

2. Select best BS(s) per 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 the number of layers per UE (SU-MIMO setting) - 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 twice as much power per antenna element as the power used in dual-layer transmission. The selected polarisation in the BS for a single-layer transmission is the one that has the highest SINR to the UE, while in the dual-layer transmission there will be a bitrate per data stream. Therefore, the single-layer stream will have an higher bitrate that each of the streams in a dual-layer mode, but the aggregation of the two stream in dual-layer transmission may total more bits across.

   The process to estimate the achievable bitrate from a SINR is used later once more, and is done taking into account the number of PRBs scheduled UE. We use wideband scheduling, attributing all resources to every transmission, hence the number of PRBs in the available band is used for scaling the bitrate.

   The procedure for bitrate estimation is the following:

   (a) Use the SINR to estimate the MCS from the MCS curves - the first Channel Quality Indicator (CQI) that achieves a lower percentage of block errors than the BLER target $BLER_{target}$ is chosen. Represented in Figure 1.1 are the BLER curves for all CQIs considered. The point at which each MCS curve intercepts the BLER probability of 10% is marked. The MCS that corresponds to each CQI index is present in Table 1.1.

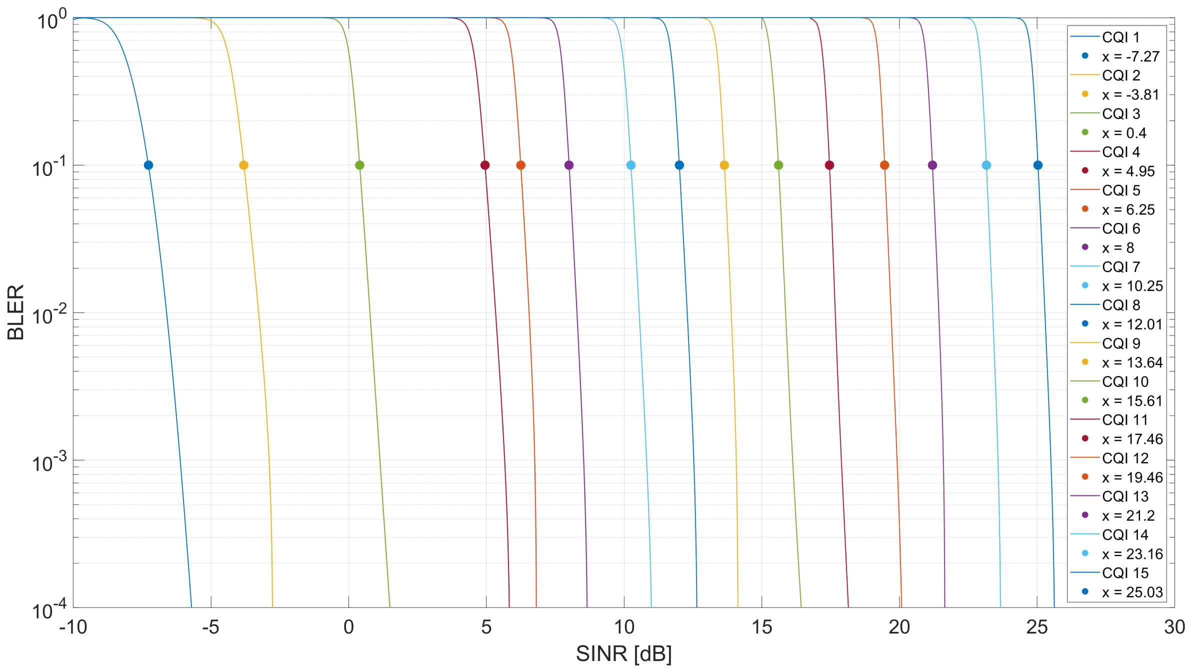

Figure 1.1: BLER curves for all MCSs. Simulated with Vienna Link-Level Simulator [3].

(b) Adjusts the choice of Modulation and Coding Scheme (MCS) with the UE-specific Outer Loop Link Adaptation (OLLA) parameter - every time a MCS is estimated, it is adjusted with the OLLA parameter at the last step. The OLLA parameter for a UE is initialised at zero and is updated in each TTI the given UE is scheduled (see Equations (1.4) and (1.5) at the end of the section). The parameter adjusts the MCS choice by flipping an appropriately biased coin and summing either $\lfloor\Delta_{OLLA}\rfloor$ or $\lceil\Delta_{OLLA}\rceil$ to the CQI index estimated in the previous step. An appropriately biased coin in this situation is a coin that selects to round down the OLLA parameter with a probability of $\lceil\Delta_{OLLA}\rceil - \Delta_{OLLA}$. This makes sense because Δ_{OLLA} is decreased when a block has errors, thus making more likely that the MCS is reduced when the link has worse quality than expected. When the block doesn't have errors, it makes it more likely to increase the MCS estimate, such that a good link condition can be taken advantage of to increase the bitrate. Note that this formulation still works as supposed for negative values.

(c) From the newly adjusted MCS and the assigned resources, estimate the achievable bitrate - We need a set of MCSs from which to choose MCSs. In [4] there are several tables with different sets MCSs, and we've picked Table 5.2.2.1-3 because it is the only one that has 256QAM modulation, the highest modulation order in 5G. This is something we want because the setting should allow very high SINRs and we don't want to limit the maximum bitrate by using a lower MCS than it would be possible to use. Table 1.1 shows the previously mentioned MCS table and includes the ideally achieved throughputs, when all resource elements are used for data transmission. The last column of the table is obtained for one PRB-worth of REs (12 subcarriers used for the duration of 14 symbols results in 168 time-frequency resource elements, or symbols). Thus, we consider 168 symbols for data in each PRB ($\mathrm{N}_{\text{symb}}^{\text{PRB}} = 168$). Since each symbol codes $\log_2(M)$ bits, where M is the modulation order, we get the number of information bits transmitted per symbol $N_{\text{info bits}}^{\text{symb}}$ from multiplying the number of bits coded in each symbol $N_{\text{bits}}^{\text{symb}}$ to the code rate R_{c} (percentage symbols used for information) - results in the efficiency column. From the product of the efficiency with $N_{\text{symb}}^{\text{PRB}}$, we obtain the bits per slot $N_{\text{bits}}^{\text{slot}}$, which is independent of the numerology. Dividing by the slot duration T_{slot} we obtain the bitrate R_{B}. Equation (1.3) sums up this process.

$$R_{\mathsf{B}} = \frac{\log_2(M) \times N_{\mathsf{bits}}^{\mathsf{symb}} \times R_{\mathsf{c}} \times N_{\mathsf{symb}}^{\mathsf{PRB}}}{T_{\mathsf{slot}}} \tag{1.3}$$

Table 1.1: Table 5.2.2.1-3 from [4] with the maximum possible bitrate in a 1ms slot.

CQI index	Modulation	Code rate x 1024	Efficiency	Bit Rate [kbps]
0	out of range			
1	QPSK	78	0.1523	25.59
2	QPSK	193	0.377	63.33
3	QPSK	449	0.877	147.33
4	16QAM	378	1.4766	248.06
5	16QAM	490	1.9141	321.56
6	16QAM	616	2.4063	404.25
7	64QAM	466	2.7305	458.72
8	64QAM	567	3.3223	558.14
9	64QAM	666	3.9023	655.59
10	64QAM	772	4.5234	759.94
11	64QAM	873	5.1152	859.36
12	256QAM	711	5.5547	933.19
13	256QAM	797	6.2266	1046.06
14	256QAM	885	6.9141	1161.56
15	256QAM	948	7.4063	1244.25

4. Compute UE priorities based on the estimated instantaneous bitrate - provided that our traffic is all real-time traffic from the application, and given that our application is very latency-constrained, [5] advises the use of a latency aware scheduler and shows that Maximum-Largest Weighted Delay First (M-LWDF) performs better than Exponential/Proportional Fair (EXP/PF).

   verify after results if this is also the scheduler that works (the best) and put formula of the final decision

5. Select which users to co-schedule (MU-MIMO setting) - to list the users to be scheduled together until the next update to the schedule. The co-scheduling rule for a single-BS operation is to add one UE layer at a time to the list, by order of UE priority (computed in the previous step), if the best beams used for those layers are compatible with the previously added UE layers. And we define as compatible beams when the BS-side beam, belonging to the GoB is at least 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, so are still used together. Beams located diagonally adjacent of the GoB are considered to have a distance of 2, hence they may be co-scheduled when $k \leq 2$. Figure 1.2 illustrates the beams that can't be co-scheduled with certain values of k, representing in filled circles as incompatible beams, and empty circles as compatible beams with the central orange beam. More generally,

the beam distance is defined by the sum of absolute differences of the beam indices in the grid. Mathematically, the beamformers $p_{i,j}$ and $p_{i',j'}$, having (i, j) and (i', j') as the GoB indices, respectively, are compatible if $|i-i'|+|j-j'| \geq k$.

IMPORTANT!!!!!! There's quite a big problem here. How to know if both layers can be co-scheduled or not? This actually starts in the SU-MIMO setting: just having different polarisations does not guarantee enough orthogonality such that the interference is insignificant/bearable!

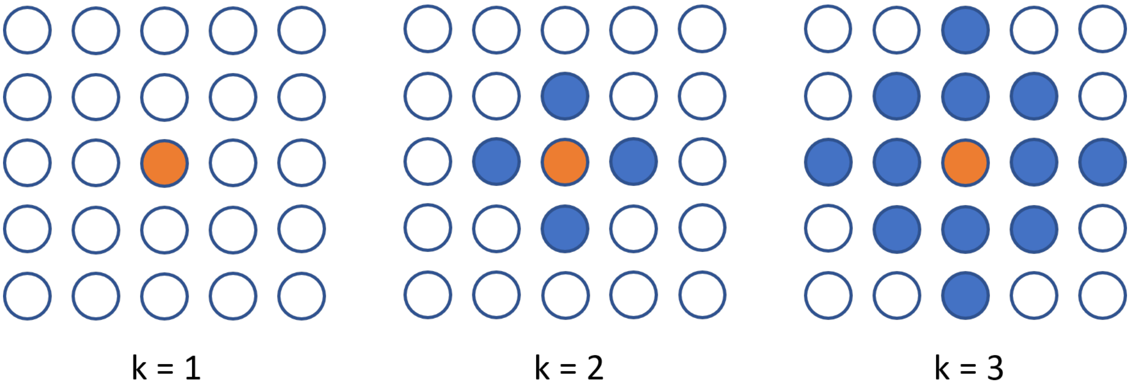

Figure 1.2: adf

7. Power control - Depending on the beamforming strategy, it may be necessary to scale down all precoders due to excessive power constraints. This, however, does not concern us because hour beamformers always have uniform amplitude. The power control process in the downlink is as simple as distributing the maximum total transmit power equally amongst the scheduled UEs, and equally amongst UE layers. In case of UL, the process is a tad more complex.........

8. Re-estimate the SINRs, per UE, per layer - the power to be used in each layer is now known, and the assigned spectrum per UE is also known (applicable in UL since DL performs wideband scheduling).

9. Choose the final MCS, per UE, per layer, based on the last SINR estimate (analogous to the third step).

1.1.3 Simulating the TTI

At the end of the processing per TTI, it is time to obtain the outcomes of the realised transmissions: the SINRs each UE got in each layer in each PRB and how those resulted in the success or failure of the transport blocks. The steps follow:

1. Obtain the Transport Block Size (TBS) from the MCS used and the allocated number of PRBs - Table 1.1 has the . There's a TB per bandwidth part.

   The number of bits is the numerator in Equation (1.3)

   The TBS

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. Aggregate/compress the vector of realised SINRs (one SINR per PRB) into a single effective SINR for the transmission - this is done with Mutual Information Effective SINR Mapping (MIESM) suggested by [6] and [7]. We choose this SINR mapping strategy because [7–11] make a compelling case in favour of this mapping method, showing that it unquestionably achieves the very good results without the need of calibration for different MCSs. We confirmed the results and present a clear description of how it works in Appendix [**?**].

4. Compute BLER from $SINR_{\text{eff}}$ and the MCS used for the transmission by using curve with the correspondent CQI index in Figure 1.1.

5. Flip a BLER-biased coin to determine if each block was well received or had errors.

6. Update the OLLA parameter based on success or not from the block transmission - the OLLA parameter is updated when Transport Block (TB) has errors or when a TB is successfully transmitted. Equations (1.4) and (1.5) show the how Δ_{OLLA} is updated when the block is successfully transmitted and when the block has errors, respectively. Observe the subtlety of the asymmetry in update. The term that multiplies the step size γ_{OLLA} is much bigger in (1.5) than in (1.4), since $BLER_0$ is usually 0.1 or smaller. It's a defensive approach, to take bigger steps when there are errors: because it is always better to have some bitrate than no bitrate.

This approach is too greedy when all information goes in one transport block, because it increases the MCS until there's an error. We have to have several transport blocks in order to avoid converging to a no-bitrate TTI. With more transport blocks, it's possible to have some errors but still a quite good bitrate. The step-size should accout for how many transport blocks we have since we are updating the OLLA param per transport block..

$$\Delta_{OLLA} = \Delta_{OLLA} + BLER_0 \times \gamma_{OLLA} \tag{1.4}$$

$$\Delta_{OLLA} = \Delta_{OLLA} - (1 - BLER_0) \times \gamma_{OLLA} \tag{1.5}$$

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