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Title: **Discussion on DL beam management**
Agenda Item: **7.1.2.2.1**
Document for: **Discussion and Decision**

1. Introduction

In this contribution we discuss several outstanding issues regarding DL beam management including beam reporting format, DL beam indication, and switching time between NR-PDCCH/NR-PDSCH for analog Rx beamforming. DL beam failure/recovery is another important aspect of beam management and will be discussed in a separate paper.

Selected agreements in previous meetings are provided below, for easy reference.

Working assumptions:

- Support at least one of these two alternatives of beam reporting:
  - Alt 1:
    - UE reports information about TRP Tx Beam(s) that can be received using selected UE Rx beam set(s).
      - where a Rx beam set refers to a set of UE Rx beams that are used for receiving a DL signal
        - Note: It is UE implementation issues on how to construct the Rx beam set.
        - One example: each of Rx beam in a UE Rx beam set corresponds to a selected Rx beam in each panel.
      - For UEs with more than one UE Rx beam sets, the UE can report TRP Tx Beam(s) and an identifier of the associated UE Rx beam set per reported TX beam
      - NOTE: Different TRP Tx beams reported for the same Rx beam set can be received simultaneously at the UE.
      - NOTE: Different TRP TX beams reported for different UE Rx beam set may not be possible to be received simultaneously at the UE
  - Alt 2:
    - UE reports information about TRP Tx Beam(s) per UE antenna group basis
      - where UE antenna group refers to receive UE antenna panel or subarray
      - For UEs with more than one UE antenna group, the UE can report TRP Tx Beam(s) and an identifier of the associated UE antenna group per reported TX beam
      - NOTE: Different TX beams reported for different antenna groups can be received simultaneously at the UE.
      - NOTE: Different TX beams reported for the same UE antenna group may not be possible to be received simultaneously at the UE
- FFS: How UE antenna group or Rx beam set is captured in the specification

Agreements:

- *Confirm the working assumption on group based beam reporting made in RAN1 Jan. NR Adhoc Meeting, with the following update:*
  - *Further discussion for possible down-selection or merging, especially taking into account overhead*

Agreements:

- *NR supports the following beam reporting considering L groups where L>=1 and each group refers to a Rx beam set (Alt1) or a UE antenna group (Alt2) depending on which alternative is adopted.*
  - *For each group l, UE reports at least the following information:*
    - *Information indicating group at least for some cases*
      - *FFS: condition(s) to omit this parameter e.g. when L=1 or N_l=1*
    - *Measurement quantities for N_l beam (s)*
      - *Support L1 RSRP and CSI report (when CSI-RS is for CSI acquisition)*
        - *FFS: the details of RSRP/CSI derivation and content*
        - *FFS: Other reporting contents, e.g., RSRQ*
        - *FFS: Configurability between L1 RSRP and CSI report*
        - *FFS: whether or not to support differential L1 RSRP feedback*

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- *FFS: How to select N_l beam(s) e.g max N_l beams in terms of received power being above a certain threshold or in terms of correlation less than a certain threshold*
  - *Information indicating N_l DL Tx beam(s) when applicable*
    - *FFS: the details on this information, e.g., CSI-RS resource IDs, antenna port index, a combination of antenna port index and a time index, sequence index, beam selection rules for assisting rank selection for MIMO tx, etc.*
- *This group based beam reporting is configurable per UE basis.*
  - *This group based beam reporting can be turned off per UE basis e.g. when L=1 or N_l=1*
    - *NOTE: No group identifier is reported when it is turned off*
  - *FFS: how L is determined. e.g. by network configuration or UE selection or UE capability e.g. how many beams can be received simultaneously*
  - *FFS: how is configured using the CSI framework to support multi-panel or multi-TRP transmission*

2. Discussion

It has been agreed in RAN1#88bis that CSI and beam measurement will be using the same framework. Note that it does not imply CSI reporting and beam reporting are necessarily the same procedures. They can still be configured as different procedures, using the common framework. Alternatively it is also possible to combine CSI and beam reporting in one procedure so that the network acquire CSI and beam reporting in a "one-shot" uplink feedback.

One illustrative example of configuration is given in Figure 1. Resource setting 1 includes configurations of CSI-RS for beam management, and CSI reporting setting is linked to Resource setting 1. CSI parameter for CSI reporting setting 1 is configured as e.g., RSRP and CRI. Therefore, based on CSI reporting setting 1 and Resource setting 1, UE can perform beam reporting. CSI Reporting setting 2 is used for CSI acquisition and is also linked to Resource setting 1. When CSI-RS for beam management has multiple antenna ports, it can also be used for CSI acquisition. That is, Resource setting 1 is used for both beam management and CSI acquisition. Resource setting 3 is for interference measurement and both CSI reporting setting 2 and 3 are linked to Resource setting 3.

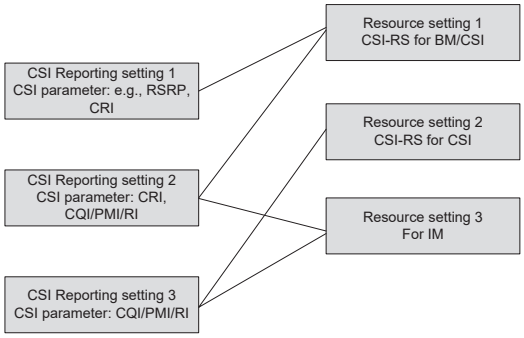

Figure 1: Example of CSI acquisition framework configuration

2.1. Measurement quantities

Measurement quantities for the selected beams can be CSI or RSRP. With CSI measurement, the preferred beams and CSI over the beam are acquired at gNB in a single step. Data transmission can follow the beam reporting immediately utilizing complete CSI. However, computational complexity of deriving CSI would be a great burden for UE especially when a huge number of beams are involved. On the other hand, calculating RSRP is relative easy from complexity perspective. Another step is needed for UE to report CSI on the preferred beams if only RSRP is reported. As a result, measurement and reporting RSRP is suitable for initial beam reporting where large number of beams are to be measured. CSI can be employed in the procedure of fine beam tuning, e.g., during procedure P-2. Therefore, the measurement and reporting quantities is preferred to be configurable depending on the procedure of beam management. In some cases, reporting both CSI and RSRP may be beneficial to facilitate the comparison between beams reported during different procedures. It is straightforward to apply the agreed framework for CSI acquisition to beam reporting: whether CSI or RSRP (or both) is to be reported is configured in the CSI Reporting setting.

Proposal 2:

- *Measurement quantities for beam reporting is configurable, including RSRP, or CSI, or both RSRP and CSI.*

2.2. Information indicating selected DL Tx beams

The selected Tx beams can be indicated by CSI-RS resource IDs. CSI-RS for one candidate Tx beam is transmitted over one CSI-RS resource. The number of antenna ports for the CSI-RS resource can be configured depending on whether CSI or RSRP is reported. If only RSRP is reported, the port number could be 1 or 2. If CSI is reported, larger port number can be configured. CSI, including PMI, RI, CQI, etc, is measured and reported based on a proper codebook. This is analogous to Class B K>1 case in LTE. Antenna port index indication is similar to CSI-RS resource ID, if antenna port number of CSI-RS resource is 1.

One possibility of transmitting CSI-RS is to configure one CSI-RS resource and transmit CSI-RS over different beams at different time instances. In this case, different beams are TMD-ed in the same CSI-RS resource on different subframes. This is analogous to LTE Class B CSIRS pooling which helps to reduce the number of CSI-RS resources. CSI-RS resource ID alone is not enough to distinguish Tx beams. Therefore, time domain information is needed. To provide time domain information, a reference time domain window of certain length can be configured. UE selects and reports Tx beams by measuring the CSI-RS transmitted within the reference time window. All instances of the CSI-RS resources in the time window are referred, for example CSI-RS resource first, and the time domain index second. An example is shown in Figure 2. Two CSI-RS resources are configured and within the reference time window, each CSI-RS resource has 8 instances. The total 16 instances are numbered from 0 to 15. UE uses 4 bits to jointly indicate the CSI-RS resource and time domain information.

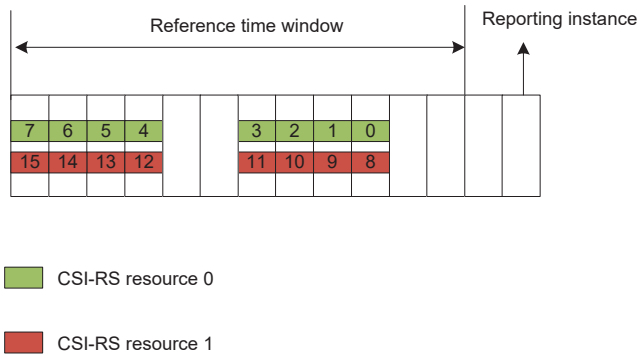

Figure 2: Reference time window configuration for indication of DL Tx beam

Proposal 3:

- *CSI-RS resource IDs and time index can be reported to indicate selected DL Tx beams.*

2.3. Beam reporting format

A BPL is defined "*by a UE or gNB measurement on a reference signal transmitted/received according to a Tx/Rx spatial filtering configuration*". Tx/Rx filtering is communicated in the form of beam reporting, e.g. as {*Beam-quality-info, Tx-beam-info, Rx-beam-info*}, where

- *Beam-quality-info* is RSRP or CSI,
- *Tx-beam-info* is the indication of Tx beam, e.g. CSI-RS resource index or time index,
- *Rx-beam-info* carries **explicit** or **implicit** information of the Rx beam. With explicit Rx beam reporting, Rx-beam-ID is explicitly known to the gNB. With implicit Rx beam reporting, BPLs are grouped based on to their associations with selected Tx beams, while Rx-beam-ID is unknown to gNB.

2.3.1 Implicit Rx-beam reporting (e.g. group based reporting)

Implicit Rx-beam reporting includes group based beam reporting, where different Tx beams are partitioned based on their mapping to the Rx beam The partition index (e.g. group index) is reported implicitly as opposed to explicit Rx-beam-ID reporting. Hence, Rx-beam-info is quantized in the form of group-ID.

In this approach the UE is responsible for making much of the Tx beam pairing decisions, based on their association to the Rx beam which is only known to the UE. Inevitably this reduces the amount of beam information that the gNB may have, and hence reduces gNB scheduling flexibility.

Conclusions: *Group-based (implicit) beam reporting limits gNB scheduling flexibility, as much of the beam paring decisions are pre-made at UE, unknown to gNB.*

Two alternatives for group-based implicit beam reporting include:

- **Alt-1**: Each group refers to an Rx beam set. Different TRP Tx beams reported for the same group can be received simultaneously at the UE.
- **Alt-2**: Each group refers a UE antenna group. Different TX beams reported for different antenna groups can be received simultaneously at the UE.

Both alternatives aim at providing gNB additional information about which Tx beams can be used simultaneously. By Alt-1, the possible combinations Tx beams are given explicitly. The combinations are given implicitly by Alt-2, that is any Tx beams belonging to different groups can be used simultaneously. In this sense, Alt-2 is more flexible and incurs less overhead than Alt-1.

An example given in Figure 3 can illustrate the situation. There are two TRPs each with four candidate Tx beams in the example. UE is capable of forming two Rx beams simultaneously using two antenna groups; therefore the UE can receive data streams transmitted from the two TRPs simultaneously. Assuming two Tx beams from TRP1 are selected, and UE receives the two Tx beams using antenna group 1. Similarly, two Tx beams from TRP2 are selected, and the UE uses antenna group 2 to receive the Tx beams. According to Alt-2, the four selected Tx beams are put into two groups, and each group consists of 2 Tx beams. Upon reception of the UE reported information, gNB can freely choose one Tx beam from each group to perform multi-beam transmission as Tx beams from different groups can be received simultaneously. There are four possible combinations of Tx beams available at gNB side. In order to achieve the same number of Tx beam combinations, Alt-1 needs at least four groups. The overhead is clearly higher than Alt-2.

Another claimed benefit of Alt-1 is that gNB can switch Tx beam in the same group without spatial QCL assumption indication to UE as the Rx beam set is the same for all Tx beams in the same group. When the Tx beams in the group are not used simultaneously, it is not necessary for the UE to use all Rx beams in the Rx beam set. Without indication of spatial QCL assumption regarding the specific used Tx beams, UE cannot set Rx beam properly. Moreover, when Tx beam is switched, the propagation path of the signal may also change. As a result, QCL assumption with respect to time/frequency parameters still has to be indicated to UE. The indication shall be related to the selected Tx beam, i.e., related to an RS transmitted from the Tx beam. That is, information regarding the Tx beam anyway needs to be signaled to UE.

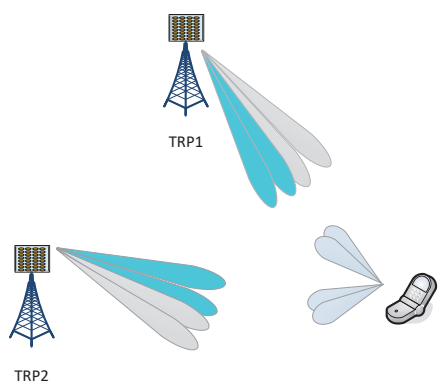

Figure 3: Illustration of group based beam reporting

In the following the feedback overhead of these two alternatives are compared. At the transmitter let the number of candidate Tx beams per panel and number of panels be denoted as N_T and P_T. At the receiver let the number of candidate Rx beams per panel and number of panels be denoted as N_R and P_R.

- For Alt-1 (beam set based grouping), each Rx beam set comprises P Rx beams where each beam corresponds to a panel. Note that P can be anywhere between 1 and P_R. As such the number of possible Rx beam sets (for quantize the *Rx-beam-info*) is $\binom{P_R}{1}N_R + \binom{P_R}{2}N_R^2 + \binom{P_R}{3}N_R^3 + \ldots \binom{P_R}{P_R}N_R^{P_R}$. Then denoting the number of reported Tx beams as M, the feedback overhead (excluding RSRP) is

$$M \times \left(\log_2(N_T P_T) + \log_2(\binom{P_R}{1} N_R + \binom{P_R}{2} N_R^2 + \binom{P_R}{3} N_R^3 + \ldots \binom{P_R}{P_R} N_R^{P_R}) \right).$$

After gNB receives the beam report, Tx beams corresponding to the same Rx beam set can be scheduled concurrently. However this is a necessary but insufficient condition for Tx beam pairing. For instance assume there are $P_T = 2$ Tx panels, and each panel has $N_T = 4$ Tx beams, there are a total of 16 possible Tx beam combinations. If the UE is configured to report $M = 2$ Tx beams, these two Tx beams, even if they correspond to the same Rx beam set, cannot be scheduled together unless they belong to different Tx panels. However from the UE's perspective it has no information whether the Tx beams (e.g. CSI-RS resources ID) are of the same panels or not, because the association between CSI-RS and antenna panels is entirely gNB implementation. If any two Tx beams in a Tx beam group recommended by UE happens to be not able to be transmitted simultaneously by gNB, the reporting is then useless. Without any guidance from gNB, this probability would be high. As can be seen, Tx beam pairing suffers in terms of feedback overhead and scheduling flexibility.

- For Alt-2 (antenna group based reporting), each group corresponds to an Rx antenna group (e.g. Rx panel). If two Tx beams correspond to the different Rx groups they can be scheduled concurrently. Using the same notation for Alt-1, the total reporting overhead (excluding RSRP) is $M \times (\log_2(P_T N_T) + \log_2(P_R))$. In contrast to Alt-1, even UE does not know which Tx beam can be used simultaneously, gNB can make proper pairing based on UE reporting.

Observation:

- *Alt-1 incurs higher reporting overhead, compared to Alt-2.*
- *Alt-1 reduces gNB complexity of beam selection, compared to Alt-2.*

The motivation of group based beam reporting is to support multi-beam spatial multiplexing. However the information reported from beam management procedure is not sufficient. For example, interference between the beams (data layers) and interference suppression capability at receiver is not taken into account during beam grouping and reporting. In order to make reliable decision on beam pairing for spatial multiplexing, CSI acquisition procedure shall be involved. That is, after initial beam reporting, CSI-RS shall be configured (transmitted) with tentative beams paired by gNB based on beam reporting, and then based on additional CSI reporting the gNB can properly conduct spatial multiplexing using different beams. Ultimately, whether the beams are suitable to be paired and the link quality of spatial multiplexing (e.g., MCS) is obtained from CSI acquisition procedure, while beam management procedure alone is insufficient. The group based beam reporting provides course information for gNB to carry out initial pairing. The Tx beams that are highly correlated and hence not suitable for spatial multiplexing will be ruled out at this stage. Alt-1 also limits the flexibility of CSI-RS configuration/transmission for CSI acquisition.

In terms of beam indication (spatial QCL assumption indication) overhead, both alternatives are similar. For Alt-1, group ID instead of Tx beam ID can be used for indication purpose. The overhead can be smaller than Alt-2 if all Tx beams in the same beam group are always used simultaneously. On the other hand the scheduling capability is severely restricted. For example, gNB may want to use some Tx beams in the beam group to serve another UE to realize MU-MIMO transmission. If only group ID is conveyed to UE, UE would by default use all Rx antenna groups to receive the signal. In MU-MIMO transmission, the UE would suffer strong interference from the panel (TRP) serving other UE as one of the Rx beam is pointing to the panel (TRP). In this case, if Tx beam ID(s) is indicated to UE, UE can choose proper Rx beam to receive the signal while avoiding receiving strong interference signal. In other words, indication overhead of Alt-1 is lower by sacrificing flexibility and/or performance. With same level of flexibility and performance, the overhead of the two alternatives would be similar.

Observation:

- *Beam pairing decision for spatial multiplexing shall be made based on CSI reporting from CSI acquisition procedure,* while beam management procedure alone is insufficient.
- *Beam indication (spatial QCL assumption indication) overhead would be similar for Alt-1 and Alt-2 if same level of flexibility and performance is aimed at.*

Proposal 4:

- *For implicit Rx-beam-info reporting, support UE antenna group (Alt2) based reporting.*

2.3.2 Explicit Rx-beam reporting

Group-based reporting Alt-2 has the benefits of reduced beam reporting overhead, but in some cases it limits gNB beam pairing flexibility. This is due to the fact that only group index (e.g. "panel index") is reported while explicit Rx-beam–ID within each group is not available at gNB. Rx-beam-ID determines whether or not Tx beams can be truly paired together. In some cases such lack of Rx-beam information may result in incorrect beam pairing decisions.

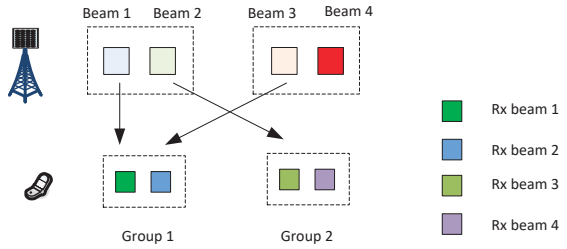

Figure 4: Example of beam grouping Alt-2 (subarray)

Table I: Exemplary group reporting scheme Alt-2

TX BEAM ID	RSRP	GROUP ID	RX-BEAM-ID
1	-80dBm	1	1
3	-85dBm	1	1
2	-90dBm	2	3

An example is provided in Figure 4, where the gNB has 2 panels with 2 Tx beams each. gNB transmits 4 CSI-RSs for measuring 4 beams. The UE has 2 Rx panels where each panel has 2 candidate Rx beams. Assume the UE report $L = 3$ beams with RSRP value and group ID in Table I. If Rx-beam-ID is not explicitly reported, because Tx beams associated with different group IDs are allowed to be paired, gNB may attempt to schedule Tx beam pairing from one of the following two candidates

- [(1, 2)]
- [(2, 3)]

Beam 1 and beam 3 cannot be scheduled at the same time because they have the same group ID. However, if Rx-beam-ID is allowed to be reported (in addition to Group-ID report), the gNB may additionally consider pairing Tx beam as

- [(1,2,3)]

where Tx beam 1 and Tx beam 3 are to be scheduled concurrently to Group 1 (using same Rx beams), and Tx beam 2 is to be scheduled to Group 2 (to be received with Rx-beam-3). As can be seen, further reporting the Rx-beam-ID provides more beam paring flexibility. The key issue here is that the Rx-beam is divided into multiple subspaces (e.g. groups) while gNB has only the subspace information but not the Rx beam information in each subspace. This is contrast to Tx beam where unquantized Tx-beam-ID is reported. If Rx-beam-ID is reported such restriction can be alleviated. The reporting can take one of three formats (to be decided):

- {Rx-beam-ID}, e.g. all Rx beams in all panels creates a single quantization alphabet
- {Group-ID, Rx-beam-ID}: where group-ID refers to UE antenna panels/subarrays, and Rx-beam-ID is the indexing within each panel.
- {Group-ID, Subgroup-ID}: where group-ID refers to UE antenna panels/subarrays, and Tx beams in the same group are further divided into subgroups. Tx beams belong to the same subgroup can be received simultaneously. Note that, this can be regarded as a merged approach of Alt-1 and Alt-2, i.e., merging Alt-1 into Alt-2.

Proposal 5:

- *Support Rx-beam-ID or Subgroup-ID reporting for DL beam management.*

2.4. Beam indication (QCL)

It was agreed in RAN1#88 that indication of spatial QCL assumption between DL RS antenna port(s) and DMRS antenna port(s) of DL data channel is supported for the reception of unicast DL data channel. The indication is via DCI (downlink grants).

2.4.1 Beam indication configurability

The indication is intended for UE to set the analog Rx beam, only when UE intends to perform analog Rx beam sweeping. Otherwise if the UE is incapable of analog Rx sweeping or does not intend to activate analog Rx beam sweeping, beam indication is not needed. Therefore, the indication shall be configurable.

Proposal 6:

- *The indication of spatial QCL assumption shall be configurable.*

2.4.2 Beam indication format

Beam indication can be explicit or implicit.

With explicit indication, the indication is to explicitly assign each beam in the network an unique index, and the index is related to some RS antenna ports. The index is used explicitly in the indication. However, the number of beams could be large, and setting a limit on the number of beams to support would limit the flexibility of the network. Moreover, the overhead of signalling the beam index in the DCI or MAC CE could be prohibitively large.

With implicit implication, Tx beam is indicated implicitly as a function of another system parameter (e.g. last reported Tx beam). For instance a BPL tag is contained in the trigger signaling of beam reporting. For each triggered measurement of CSI-RS resources, the UE reports a preferred beam (CRI) and stores the preferred UE Rx beam for that preferred beam. The BPL tag is then used to refer to this preferred Tx beam at a later point in time for QCL purposes. The pros and cons of implicitly indication include:

Pros:

- Reduced overhead. However, the coverage of NR-PDCCH should be considered from a holistic perspective by taking into account all factors in NR system design. At this moment it is difficult to quantitatively assess the impact of QCL indication alone to NR-PDCCH.

Cons:

- *Beam misalignment:* An implicit beam indication can only point to the latest reported Tx beam from the UE. This mandates the UE/gNB to have perfectly aligned understanding of the "latest beam report". In case beam report is incorrectly decoded by the gNB, misalignment on the "latest Tx beam" will degrade the system performance.
- *Limited scheduling flexibility*: For each triggered measurement, only one preferred Tx beam can be selected and reported, as one BPL tag is unable to label multiple Tx beams. Second, the gNB must use the UE's preferred Tx beam for later transmission, otherwise, the UE cannot set proper Rx beam. This incurs limitation on network flexibility. When two UEs' preferred Tx beams are different, the data channel of the two UEs cannot be multiplexed in frequency domain.

To avoid unnecessary restriction on network flexibility and system performance our preference is to explicitly indicate the DL RS antenna ports that are QCL-ed with DMRS antenna port(s) of DL data channel with respect to the spatial QCL parameter.

Proposal 7:

- *DL RS antenna ports are explicitly indicated for spatial QCL assumption.*

2.4.3 RS type for beam indication (QCL)

For spatial QCL assumption indication, two types of RS can be considered as the DL RS antenna ports. The first type is RS for mobility purpose, or mobility RS. The mobility RS could be NR secondary synchronization signal (SSS) and CSI-RS according to agreements made in RAN1#88 meeting. In multi-beam system, NR SSS can be considered as always-on signal. It seems ideal for tracking spatial QCL parameters. However, NR SSS is for broadcast purpose and may be transmitted with beam wider than data channel to limit the number of SS blocks. As a result, spatial parameter, i.e., Rx beamforming, measured on NR SSS may be not suitable for reception of data and control channel.

The second type is CSI-RS for beam management. Three beam management procedures are defined as P-1, P-2 and P-3. P-1 is used to support selection of TRP Tx beams/UE Rx beam(s). P-2 is used to determine TRP Tx beams and can be a special case of P-1. P-3 is used to enable UE Rx beam changing. By procedure P-1, UE needs to determine its own Rx beam in addition to Tx beam of TRP. The CSI-RS for P-1 shall consider UE's need to test different Rx beams. With analog beamforming at UE side, UE can only test one analog beam at one time. Therefore, the CSI-RS shall meet the requirement of Rx beam determination. A straightforward way of Rx beam determination is to repeat CSI-RS of every Tx beam multiple times so that the UE could test and select proper Rx beams. By receiving these CSI-RS, UE could determine preferred Tx beams and corresponding Rx beam. In that sense, UE is able to estimate the spatial parameter for determining Rx beamforming based on CSI-RS for P-1 procedure. To make it suitable for tracking spatial parameter, the CSI-RS shall be periodically transmitted or at least semi-persistently transmitted.

Proposal 8:

- *Periodically or semi-persistently transmitted CSI-RS ports are indicated for spatial QCL assumption.*

For the indication, candidate set of the RS antenna port(s) shall be configured. *K* CSI-RS resources can be configured as candidates. Each CSI-RS resource is beamformed with a candidate Tx beam. If periodic or semi-persistent CSI-RS are employed in the beam management procedures, the *K* CSI-RS resources could be selected from those CSI-RS resources for beam management based on UE reporting. That is, the *K* CSI-RS resources are configured to be overlapped with several of those CSI-RS resources. If the beam management procedure is performed based on aperiodic CSI-RS, *K* CSI-RS resources shall be transmitted additionally. Arbitrarily selected Tx beams can be applied to the CSI-RS resources. Upon the reception of the configuration, the UE starts to track the spatial parameters respectively.

Proposal 9:

- *K CSI-RS resources are configured as the candidate of spatial QCL assumption indication for DL unicast reception.*

2.4.4 Beam indication (QCL) for common data channel

Paging information, system information and RAR are going to be carried in common PDSCH. Paging information and system information shall be decodable by UEs in RRC_IDLE state. The Rx beam sweeping capability of these UEs is unknown to network, or the optimal Tx beam maintained at the gNB is outdated due to UE movement, and thus the indication is not useful. For reception of RAR, UE can use the Rx beam obtained from the reception the SS block related to Msg1. Explicit indication is not needed for RAR reception.

Proposal 10:

- *For common PDSCH carrying paging, system information (intended to UE in RRC_IDLE state) and RAR, indication of the spatial QCL assumption is not supported.*

2.5. NR-PDCCH/NR-PDSCH gap

Before NR-PDCCH carrying beam indication is successfully decoded, UE cannot adjust its analog RX according to the signaled beam in NR-PDCCH. This is fundamentally different than digital Rx beamforming where the UE can store digital samples of NR-PDSCH before NR-PDCCH decoding finishes, and decodes NR-PDSCH after NR-PDCCH decoding succeeds. Hence a gap between NR-PDCCH and its corresponding NR-PDSCH is needed, for analog Rx beamforming, to accommodate the following two aspects:

- *NR-PDCCH decoding latency*: This depends on the NR control signaling design and UE implementation. At this moment we assume 1-2 OFDM symbols are needed for NR-PDCCH decoding.
- *Analog beam switching*: This depends on UE implementation. It should be noted that switching time in the order of nanosecond is possible in realistic implementation.

Clearly, the gap between NR-PDCCH/NR-PDSCH reduces the system throughput. Several solutions are possible to address this issue:

Fast beam indication: *Beam (QCL) indication can be transmitted in NR-PDCCH in every DL slots.*

One possible solution is cross-slot scheduling where NR-PDCCH and its corresponding NR-PDSCH are in different slots, e.g. Figure 5. The advantage is that the scheduling delay between NR-PDCCH/NR-PDSCH naturally satisfies beam switching time, eliminating the gap all together. The disadvantage is increased scheduling delay for NR-PDSCH.

Another possible solution is to divide NR-PDSCH in two parts, part 1 and part 2 as shown in Figure 6. When UE decodes part 1, it uses a default Rx beam. When UE decodes part 2, it uses the Rx beam indicated in NR-PDCCH. The gap is completely eliminated. However it needs to be studied if unbalanced link quality between two parts causes any performance issue.

Observation:

- *It is possible to eliminate the gap completely (e.g. cross-slot scheduling, NR-PDSCH partitioning).*

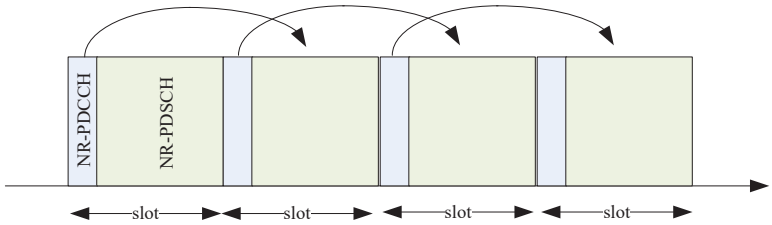

Figure 5: Cross-slot beam indication

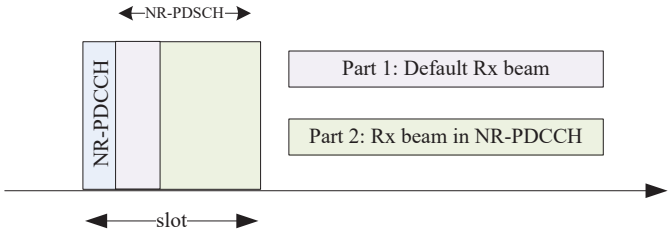

Figure 6: Beam indication based on partition of NR-PDSCH

Slow beam indication: Beam (QCL) indication can be transmitted in NR-PDCCH in a selected subset of slots. Rx beam switching and the gap between NR-PDCCH/NR-PDSCH only exist in the subset of slots.

The set of slots can be pre-configured by RRC signaling (e.g. using periodicity/offset), or dynamically indicated by another L1 control signaling. The advantage of this is that it allows the network to flexibility control the pace of beam switching, based on UE movement, beam width, and other system parameters. The disadvantage is reduced beam switching opportunity.

Another possibility is to set a timer for each beam indication, e.g. valid fur *N* slots. The value of *N* can be pre-configured or fixed in the specification, or even dynamically changes in each DCI. The disadvantage is reduced scheduling flexibility: once an Rx beam is indicated, UE must assume there is no Rx beam change until *N* slots later. Of course the gNB can always reset the Rx beam before the timer expires by sending a new QCL indication, but that is also problematic because the UE does not know in advance in which slot the gNB would attempt to overwrite the beam and hence would have to reserve a gap in every slot.

We propose to first compare fast and slow beam indication.

Proposal 11:

- *Further study fast and slow beam indication, for addressing the gap between NR-PDCCH/NR-PDSCH, considering possible*

3. Conclusions

In this contribution, further details of downlink beam management are discussed, and the following observations/proposals are noted;

Observation:

- *Alt-1grouping based beam reporting incurs higher reporting overhead and reduces scheduling flexibility, compared to Alt-2.*
- *Beam pairing decision for spatial multiplexing shall be made based on CSI reporting from CSI acquisition procedure,* while beam management procedure alone is insufficient as it doesn't consider interference.
- *Beam indication (spatial QCL assumption indication) overhead would be similar for Alt-1 and Alt-2 if same level of flexibility and performance is aimed at.*
- *Eliminating the gap between NR-PDCCH and NR-PDCH is possible, e.g. cross-slot scheduling, partitioning of NR-PDSCH.*

Proposal 1: *The agreed CSI acquisition framework is applied to downlink beam reporting.*

Proposal 2: *Measurement quantities for beam reporting is configurable between RSRP, CSI, and both RSRP and CSI.*

Proposal 3: *CSI-RS resource IDs and time index can be reported to indicate selected DL Tx beams.*

Proposal 4: *For implicit Rx-beam-info reporting, support UE antenna group (Alt2) based reporting.*

Proposal 5: *Support Rx-beam-ID or Subgroup-ID reporting for DL beam management.*

Proposal 6: *The indication of spatial QCL assumption shall be configurable.*

Proposal 7: *DL RS antenna ports are explicitly indicated for spatial QCL assumption.*

Proposal 8: *Periodically or semi-persistently transmitted CSI-RS ports are indicated for spatial QCL assumption.*

Proposal 9: *K CSI-RS resources are configured as the candidate of spatial QCL assumption indication for DL unicast reception.*

Proposal 10: *For common PDSCH carrying paging, system information (intended to UE in RRC_IDLE state) and RAR, indication of the spatial QCL assumption is not needed.*

Proposal 11: *Further study fast and slow beam indication, for addressing the gap between NR-PDCCH/NR-PDSCH.*

4. References

[1] R1-1702676, "On DL beam indication," Ericsson, Athens, Greece, 13th– 17th February, 2017