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1 Introduction

In RAN1#80, several potential enhancements targeting 2D antenna array are discussed [1]. Five high-level categories of CSI-RS and feedback enhancements were agreed in principal:

- *Enhancements related to beamformed CSI-RS-based schemes*
- *Enhancements related to non-precoded CSI-RS-based schemes*
- *Enhancements related to schemes based on hybrid beamformed CSI-RS and non-precoded CSI-RS*
- *Enhancements related to non-codebook based CSI reporting for TDD*
- *Enhancements related to SRS*

In this contribution, we discuss potential codebook enhancements for both beamformed - and non-precoded CSI-RS-based schemes.

2 Codebook design for 2D antenna array

Codebook designs have been thoroughly studied from Rel-8 throughout Rel-12. All those studies were conducted under the assumption that antenna ports are aligned in a one-dimensional array. The codebooks available in Rel-12 and pervious releases are optimized to adapt the channel variation in azimuth dimension. In elevation beamforming and full-dimensional MIMO, 2D antenna arrays are introduced to exploiting the elevation dimension in addition to the azimuth dimension. Hence, there's a need to design a new codebook for CSI reporting to capture the spatial information in both dimensions. Two alternatives can be considered for the new codebook design.

The first option is to design new codebooks for various feasible antenna port arrays, which would require lots of specification work. Not to mention that this approach may lead to prohibitive overhead in UL feedback and increase the UE complexity drastically, since the codebook size needs to be increased significantly as the number of antenna ports getting large.

Another option is to introduce a new vertical codebook on top of existing Rel-12 codebooks and to jointly use the vertical codebook and the Rel-12 codebook for CSI feedback. The reuse of Rel-12 codebooks as horizontal codebooks are possible if the number of horizontal antenna ports is 2, 4, or 8. In such case, the CSI report contains a horizontal PMI (H-PMI), a vertical PMI (V-PMI), a RI and a CQI. With separate horizontal and vertical codebooks, UE may be configured with different time-/frequency granularities for its horizontal- and vertical PMI feedback.

Observation 1: The use of separate horizontal- and vertical codebooks allows reusing of existing codebooks as well as dimension dependent feedback granularity.

As the full two-dimensional CSI is represented by one-dimensional horizontal- and vertical PMIs, how to build the composite precoding matrix needs to be specified. Since the construction of composite precoding matrix from component

PMI feedbacks introduces a structure of the resulting precoding matrix. Under the same feedback overhead constraints, a well-defined structure can achieve lower quantization error.

Observation 2: With separate codebook feedback, construction of the composite precoding matrix from component PMIs are crucial to system performance.

In the rest of this section, we discuss two options to build the composite precoding matrix from the component PMIs.

2.1 Kronecker product (KP) codebooks

In [2], the spatial covariance structure of a channel with a single dominant path is studied. It shows that the principal eigenvector exhibits a Kronecker product structure if the channel has a single dominant path. It leads to a Kronecker product structure of the composite rank-1 precoding matrix

$$\mathbf{w} = \mathbf{w}_H \otimes \mathbf{w}_V,$$

where \mathbf{w}_H is indicated by the horizontal PMI based on Rel-12 codebook and \mathbf{w}_V is indicated by the vertical PMI which could be selected from a DFT based codebook. Note that this structure is also valid for cross-polarized 2D antenna array.

In case of rank- r , the Kronecker structure can be retained by assuming a rank-1 vertical PMI, i.e.,

$$\mathbf{W} = \mathbf{W}_H \otimes \mathbf{w}_V,$$

where \mathbf{W}_H is indicated by the rank- r horizontal PMI.

To reduce the feedback overhead, the vertical PMI may be further represented by product of two matrices. Like the dual PMI feedback in Rel-12, the first matrix is indicated by a first vertical PMI and the second matrix is indicated by a second vertical PMI. The first vertical PMI is wideband-wise and the second vertical PMI can be either subband-wise or wideband-wise. Denote \mathbf{X}_H and \mathbf{Y}_H as the first and second matrices indicated by the first and second horizontal PMIs, respectively. The horizontal precoding matrix, \mathbf{W}_H , can be written as $\mathbf{X}_H \mathbf{Y}_H$. Similarly, denote \mathbf{X}_V and \mathbf{y}_V as the first and second matrices indicated by the first and second vertical PMIs, respectively. The vertical precoding matrix, \mathbf{w}_V , can be presented by $\mathbf{X}_V \mathbf{y}_V$. The composite precoding matrix can thus be rewritten as a product of two matrices as

$$\mathbf{W} = \mathbf{X} \mathbf{Y},$$

where $\mathbf{X} = \mathbf{X}_H \otimes \mathbf{X}_V$, and $\mathbf{Y} = \mathbf{Y}_H \otimes \mathbf{y}_V$.

Such KP codebook structure depends on the rank-1 vertical PMI assumption which is valid only if the antenna ports are correlated in vertical. Notice that the antenna port correlation in vertical is related to TXRU virtualization. As shown in Figure 1, effective antenna port separation is Kd_V for 1D TXRU virtualization with K antennas. If $d_V = 0.8\lambda$, the antenna port will be 1.6λ or 3.2λ for TXRUs virtualized by 2 or 4 antennas. In such cases, the antenna port correlation in vertical may be low. Hence, the rank-1 vertical PMI assumption may not hold any more.

Observation 2: KP codebook structure relies on the assumption that antenna ports are highly correlated in vertical, which may not be valid for all feasible TXRU virtualizations.

2.2 Partial Kronecker product codebooks

Since the TXRU virtualization is an implementation issue, the new codebook structure is expected to be less dependent on any specific TXRU virtualization. A unified codebook design shall be considered to support various TXRU virtualizations.

Notice that dropping the correlation constraint is equivalent to allowing heterogeneous vertical steering on different layers or even on different polarization groups. It can be achieved by relaxing the KP structure for the composition of horizontal- and vertical precoding matrices. We can still keep the KP structure at the layer level and/or at the polarization level. To reach this, we denote $\mathbf{Y}_H = (\mathbf{y}_H^{(1)} \ \dots \ \mathbf{y}_H^{(r)})$ and $\mathbf{Y}_V = (\mathbf{y}_V^{(1)} \ \dots \ \mathbf{y}_V^{(r)})$ as the matrices indicated by the second horizontal- and vertical PMIs, respectively. The composite precoding matrix is given by

$$\mathbf{W} = (\mathbf{X}_H \otimes \mathbf{X}_V) (\mathbf{y}_H^{(1)} \otimes \mathbf{y}_V^{(1)} \ \dots \ \mathbf{y}_H^{(r)} \otimes \mathbf{y}_V^{(r)})$$

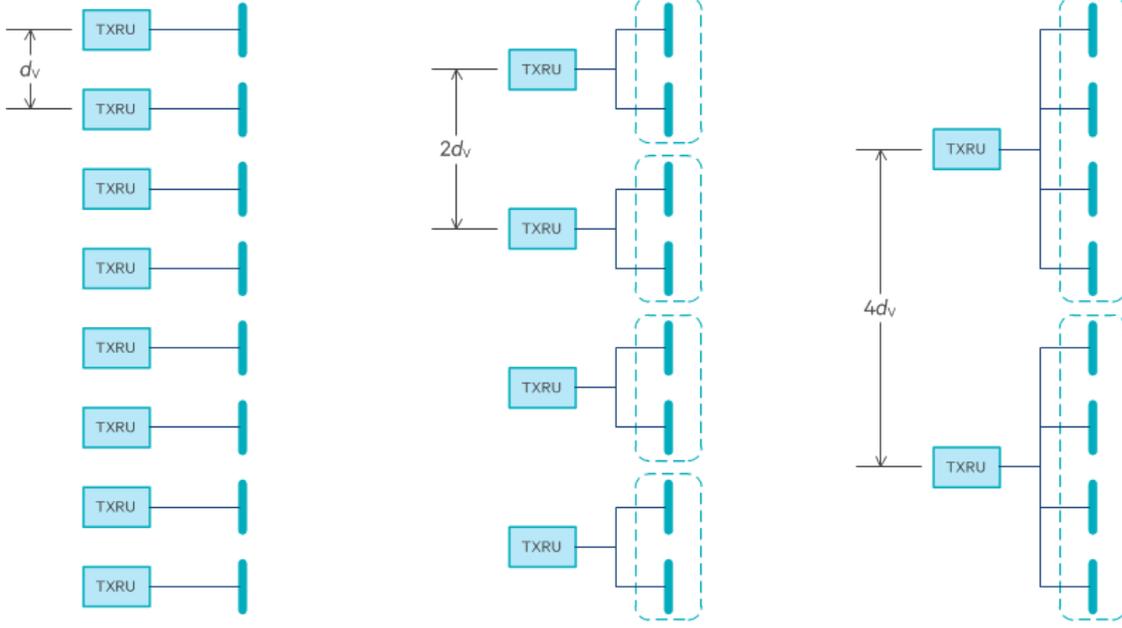


Figure 1: Vertical spacing of antenna ports for different TXRU virtualization.

For cross-polarized arrays, $\mathbf{y}_H^{(\ell)}$ can be written as $\begin{pmatrix} \mathbf{y}_{H+}^{(\ell)} \\ \phi^{(\ell)} \mathbf{y}_{H+}^{(\ell)} \end{pmatrix}$, $\ell = 1, 2, \dots, r$, where $\phi^{(\ell)}$ is the co-phasing between cross-polarized groups; $\mathbf{y}_V^{(\ell)}$ can be written as $\begin{pmatrix} \mathbf{y}_{V+}^{(\ell)} \\ \mathbf{y}_{V-}^{(\ell)} \end{pmatrix}$. In order to reuse the existing Rel-12 codebook for H-PMI feedback we assume the same steering in horizontal dimension, but for the vertical dimension we alleviate this constraint.

Keep the KP structure at a per-layer and per-polarization level, the composite precoding matrix can be written as

$$\mathbf{W} = (\mathbf{X}_H \otimes \mathbf{X}_V) \begin{pmatrix} \mathbf{y}_{H+}^{(1)} \otimes \mathbf{y}_{V+}^{(1)} & \dots & \mathbf{y}_{H+}^{(r)} \otimes \mathbf{y}_{V+}^{(r)} \\ \phi^{(1)} \mathbf{y}_{H+}^{(1)} \otimes \mathbf{y}_{V-}^{(1)} & \dots & \phi^{(r)} \mathbf{y}_{H+}^{(r)} \otimes \mathbf{y}_{V-}^{(r)} \end{pmatrix}$$

It's worth noting that KP structure is a special case of the partial KP structure. When $\mathbf{y}_V^{(1)} = \dots = \mathbf{y}_V^{(r)} = \mathbf{y}_V$, we have

$$(\mathbf{y}_H^{(1)} \otimes \mathbf{y}_V \quad \dots \quad \mathbf{y}_H^{(r)} \otimes \mathbf{y}_V) = \mathbf{Y}_H \otimes \mathbf{y}_V$$

Hence, the partial KP structure reduces to the KP structure. For cross-polarized arrays, we can have the same conclusion when $\mathbf{y}_{V+}^{(1)} = \mathbf{y}_{V-}^{(1)} \dots = \mathbf{y}_{V+}^{(r)} = \mathbf{y}_{V-}^{(r)}$.

3 Performance evaluation

To evaluate the performance benefit of partial KP structure discussed in Section 2, system-level evaluation has been performed. We have simulated two codebook structures for 16- and 64-TXRUs virtualized from an (8, 4, 2) cross-polarization 2D antenna element array. For 16-TXRU, 1D TXRU virtualization with 4 antennas is adopted, which results in a (2, 4, 2) TXRU array. For 64-TXRU, one-to-one mapping between TXRU and antenna is assumed.

Single CSI feedback is assumed. Both FTP traffic and full-buffer traffic are simulated. For non-full-buffer traffic, the packet arrival rate λ is selected such that a resource utilization of 20% is reached with the baseline scheme. We assume subband horizontal PMI feedback based on the Rel-12 8TX codebook, i.e., the horizontal PMI is comprised with a wideband first PMI and several subband second PMI.

For KP structure codebook, we use 8 DFT beams to construct \mathbf{X}_V , e.g., one group with 8 DFT beams. \mathbf{y}_V is designed to select 1 out of the 8 DFT beams. For partial KP structure codebook, we use the same 8 DFT beams to construct \mathbf{X}_V . \mathbf{Y}_V is designed

to allow layer-wise and/or polarization-wise vertical beam selection. To keep the feedback overhead comparable, there are 7 hypotheses for \mathbf{X}_V (e.g., two adjacent overlapping DFT beams per group) and 4 hypotheses for \mathbf{Y}_V . In Table 1, we summarize the feedback overhead of both KP and partial KP structure in our simulation.

Table 1: Feedback overhead comparison for KP and partial KP codebook structure.

Codebook structure	1 st V-PMI	2 nd V-PMI
KP structure	0 bits	3 bits
Partial KP structure	3 bits	2 bits

Virtual sectorization using beamformed CSI-RS resources is served as the baseline. For both 16- and 64-TXRU, 1D TXRU virtualization is applied to antennas in the same column with the same polarization. 2 and 8 vertical sectors are virtualized for 16- and 64-TXRU, respectively. Each vertical sector has 8 antenna ports. CRS port 0 is mapped to TXRUs virtualized by the same group of antennas.

The performance benefits of the proposed codebook structure is summarized in Tables 2, 3 and 4.

Table 2: Non-full buffer performance benefit with different codebook structure in 3D-UMi, 200m ISD, 2GHz (16-TXRU, $\lambda = 1.7$ packet/cell/s)

Scheme	RU [%]	5%-tile UPT		50%-tile UPT		Mean UPT	
		[Mbps]	[%]	[Mbps]	[%]	[Mbps]	[%]
Baseline	19.5	12.2	N/A	39.6	N/A	40.5	N/A
KP codebook (wideband)	16.4	13.9	13.7%	43.0	8.6%	42.2	4.1%
KP codebook (subband)	16.4	14.1	16.7%	43.5	9.8%	43.9	8.3%
(Gain over wideband KP)			(1.7%)		(1.1%)		(4.0%)
Partial KP codebook (wideband)	16.2	14.6	20.5%	48.8	20.7%	44.9	9.9%
Partial KP codebook (subband)	15.0	17.8	47.1%	49.4	22.2%	45.4	11.2%
(Gain over wideband partial KP)			(22.0%)		(1.2%)		(1.1%)

Table 3: Non-full buffer performance benefit comparison in 3D-UMi, 200m ISD, 2GHz (16-TXRU, $\lambda = 1.7$ packet/cell/s)

Scheme	RU [%]	5%-tile UPT		50%-tile UPT		Mean UPT	
		[Mbps]	[%]	[Mbps]	[%]	[Mbps]	[%]
KP codebook (subband)	16.4	14.1		43.5		43.9	
Partial KP codebook (subband)	15.0	17.8	26.0%	49.4	13.6%	45.4	3.5%

Table 4: Full buffer performance benefit with different codebook structure in 3D-UMi, 200m ISD, 2GHz

Scheme	16-TXRU		64-TXRU	
	5%-tile UE Spectral Efficiency	50%-tile UE Spectral Efficiency	5%-tile UE Spectral Efficiency	50%-tile UE Spectral Efficiency

	[bps/Hz]	[%]	[bps/Hz]	[%]	[bps/Hz]	[%]	[bps/Hz]	[%]
KP codebook (SB)	0.147		0.470		0.175		0.568	
Partial KP codebook (SB)	0.155	5.4%	0.491	4.5%	0.188	7.5%	0.601	5.8%

It shows that benefit of subband vertical PMI feedback is very sensitive to the codebook structure. With KP codebook, increase the frequency granularity of vertical PMI feedback provides very limited performance gain. However, with partial KP codebook, subband vertical PMI feedback provides significant gain at 5%-tile UPT and moderate gain at 50%-tile over both the baseline scheme and the KP structure codebook. Note that those gains are achieved even with 1 less bit subband feedback compared to KP codebook.

Observation 3: Benefit of subband vertical PMI reporting depends on the codebook structure.

Observation 4: Compared to baseline, both KP and partial KP codebooks provide significant gain at 5%-tile UPT in case of 16 TXRUs with 1D virtualization.

Observation 5: Compared to KP codebook, partial KP codebook significantly improve performance of both cell-edge and cell center users with less subband feedback overhead in case of 16 TXRUs with 1D virtualization.

Based on our observation, we propose:

Proposal 1: Subband vertical PMI feedback shall be considered at least for 16 TXRUs.

Proposal 2: Partial KP codebook structure should be considered for non-precoded CSI-RS based feedback enhancement.

4 Conclusions

In summary, we discuss codebook designs targeting 2D antenna arrays. We have following observation:

Observation 1: The use of separate horizontal- and vertical codebooks allows reusing of existing codebooks as well as dimension dependent feedback granularity.

Observation 2: KP codebook structure relies on the assumption that antenna ports are highly correlated in vertical, which may not be valid for all feasible TXRU virtualizations.

Observation 3: Benefit of subband vertical PMI reporting depends on the codebook structure.

Observation 4: Compared to baseline, both KP and partial KP codebooks provide significant gain at 5%-tile UPT in case of 16 TXRUs with 1D virtualization.

Observation 5: Compared to KP codebook, partial KP codebook significantly improve performance of both cell-edge and cell center users with less subband feedback overhead in case of 16 TXRUs with 1D virtualization.

Based on above observation, we propose

Proposal 1: Subband vertical PMI feedback shall be considered at least for 16 TXRUs.

Proposal 2: Partial KP codebook structure should be considered for non-precoded CSI-RS based feedback enhancement.

5 References

- [1] Draft report of 3GPP TSG RAN WG1 #80.
- [2] R1-150713, "Discussion on FD-MIMO codebook enhancements," Samsung.