**3GPP TSG RAN WG1 #115 R1-231xxxx**

**Chicago, USA, November 13th – November 17th, 2023**

**Agenda item:** 8.17

**Source:** Moderator (Samsung)

**Title:** Summary of discussion on multiplexing HARQ-ACK in a PUSCH

**Document for:** Discussion and Decision

# Introduction

This contribution aims to collect and summarize company views on the Rel-18 TEI issue of multiplexing HARQ-ACK in a PUSCH as discussed in [1] and [2].

Please consider entering the contact information below for better coordination for this discussion.

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| **Company** | **Contact(s)** | **Email address(es)** |
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# Background

In RAN1#113 meeting, the following agreement was made.

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| Agreement  If UCI multiplexing of different priorities is not enabled, the restriction on scheduling PDSCH after UL grant is removed for the case of PUSCH with repetitions except the first repetition   * UE generates Type-1 HARQ-ACK codebook according to the existing specification with the modification of setting the actual ‘ACK/NACK’ value corresponding to PDSCH(s) scheduled after the UL grant. * UE generates Type-2/3 HARQ-ACK codebook according to the existing specification.   + For Type-2 CB, UL DAI is used for generating HARQ CB. * This feature is subject to separate UE capabilities for type-1, type-2, and type-3 codebooks. * RRC parameter(s) to configure the function of scheduling PDSCH after a UL DCI format and multiplexing associated HARQ on a PUSCH repetition except the first repetition are introduced in Rel-18. * Note: the number of PUSCH repetitions can be scheduled/configured by gNB. * Note: same principle of current specification which UL DAI in UL grant is applied to each PUSCH repetition is reused. * The timeline specified in TS 38.213 Clause 9.2.5 are satisfied, i.e. between the last PDSCH and PUCCH, between the last PDCCH among UL grant /DL grant(s) and the earliest PUCCH or PUSCH * Additional UE capabilities are introduced to support the following functions (UE will be configured by gNB to use the following features via RRC)   + HARQ-ACK codebook size change on a PUCCH slot   + PUCCH resource change on a PUCCH slot |

In RAN1#114bis meeting, the following proposal proposed by Samsung was discussed without consensus [3].

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| **Proposal: Update the previous agreement made RAN1#113 as following,**  Agreement  If UCI multiplexing of different priorities is not enabled, the restriction on scheduling PDSCH after UL grant is removed for the case of PUSCH with repetitions except the first repetition   * UE generates Type-1 HARQ-ACK codebook according to the existing specification with the modification of setting the actual ‘ACK/NACK’ value corresponding to PDSCH(s) scheduled after the UL grant. * UE generates Type-2/3 HARQ-ACK codebook according to the existing specification.   + For Type-2 CB, UL DAI is used for generating HARQ CB. * This feature is subject to separate UE capabilities for type-1, type-2, and type-3 codebooks. * RRC parameter(s) to configure the function of scheduling PDSCH after a UL DCI format and multiplexing associated HARQ on a PUSCH repetition except the first repetition are introduced in Rel-18. * Note: the number of PUSCH repetitions can be scheduled/configured by gNB. * Note: same principle of current specification which UL DAI in UL grant is applied to each PUSCH repetition is reused. * The timeline specified in TS 38.213 Clause 9.2.5 are satisfied, i.e. between the last PDSCH and PUCCH, between the last PDCCH among UL grant /DL grant(s) and the earliest PUCCH or PUSCH * Additional UE capabilities are introduced to support the following functions (UE will be configured by gNB to use the following features via RRC)   + HARQ-ACK codebook size change on a PUCCH slot   + PUCCH time domain resource change on a PUCCH slot |

In the summitted contributions, Samsung and Ericsson further discuss the issue, the following observations and proposal are made by Samsung [1].

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| **Observation 1**: If the time domain of the PUCCH resource does not change before and after the UL grant, a UE does not need additional timeline to determine the PUSCH for HARQ-ACK multiplexing.  **Observation 2**: If the DL grant coming after the UL grant indicating a PUCCH transmission not overlapping with the PUSCH repetition and if the PDCCH reception that includes the DL grant is not earlier than a predefined timeline from the beginning of the PUSCH repetition, a UE does not have enough processing time to cancel the multiplexing of HARQ-ACK in the PUSCH repetition.  **Observation 3**: If a UE does not indicate the capability of supporting PUCCH resource change in a PUCCH slot or the capability of supporting HARQ-ACK codebook size change, the following case should be avoided by gNB.   * A UE detects a DL DCI format coming after the UL DCI format scheduling a PUSCH repetition and the DL DCI format indicates a PUCCH transmission overlapping with the PUSCH repetition and there is no PUCCH with HARQ-ACK overlapping with the PUSCH repetition before detecting the DL DCI format.   **Proposal 1: Update the previous agreement made RAN1#113 as following,**  Agreement  If UCI multiplexing of different priorities is not enabled, the restriction on DL DCI format indicating HARQ-ACK information with/without scheduling PDSCH after UL grant is removed for the case of PUSCH with repetitions except the first repetition   * UE generates Type-1 HARQ-ACK codebook according to the existing specification with the modification of setting the actual ‘ACK/NACK’ value corresponding to PDSCH(s) scheduled after the UL grant. * UE generates Type-2/3 HARQ-ACK codebook according to the existing specification.   + For Type-2 CB, UL DAI is used for generating HARQ CB. * This feature is subject to separate UE capabilities for type-1, type-2, and type-3 codebooks. * RRC parameter(s) to configure the function of scheduling PDSCH after a UL DCI format and multiplexing associated HARQ on a PUSCH repetition except the first repetition are introduced in Rel-18. * Note: the number of PUSCH repetitions can be scheduled/configured by gNB. * Note: same principle of current specification which UL DAI in UL grant is applied to each PUSCH repetition is reused. * The timeline specified in TS 38.213 Clause 9.2.5 are satisfied, i.e. between the last PDSCH and PUCCH, between the last PDCCH among UL grant /DL grant(s) and the earliest PUCCH or PUSCH assuming the PUCCH indicated by the DL DCI format after UL grant overlaps with the PUSCH repetition. * Additional UE capabilities are introduced to support the following functions (UE will be configured by gNB to use the following features via RRC)   + HARQ-ACK codebook size change on a PUCCH slot   + PUCCH time domain resource change on a PUCCH slot |

In [2], the following observations and proposals are made by Ericsson.

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| **Observation 1 The condition on same codebook size is technically incorrect.**  **Observation 2 The condition on same codebook size increases UE complexity.**  **Observation 3 The condition on same codebook size makes the feature useless to be enabled.**  **Observation 4 The important factor is following the UL DAI for codebook generation before or after UL DAI, and not requiring the same codebook size before or after UL DAI**  **Observation 5 The condition on same PUCCH resource increases UE complexity.**  **Observation 6 Reusing multiplexing timeline for a PUCCH slot with HARQ-ACK before UL grant and after UL grant reduces UE complexity.**  **Proposal 1 Remove “HARQ-ACK codebook size change on a PUCCH slot” in above agreement.**  **Proposal 2 Remove “PUCCH resource change on a PUCCH slot” in the above agreement.**  **Proposal 3 Update the agreement to introduce additional capability such that the UE can reuse the multiplexing timeline for a PUCCH slot before UL grant, if the PUCCH after UL grant occurs in the same slot. The condition is the same starting time of the PUCCH resources before and after UL grant.**  **Proposal 4 Update the previous agreement as the following:**   |  | | --- | | Agreement  If UCI multiplexing of different priorities is not enabled, the restriction on scheduling PDSCH after UL grant is removed for the case of PUSCH with repetitions except the first repetition   * UE generates Type-1 HARQ-ACK codebook according to the existing specification with the modification of setting the actual ‘ACK/NACK’ value corresponding to PDSCH(s) scheduled after the UL grant. * UE generates Type-2/3 HARQ-ACK codebook according to the existing specification.   + For Type-2 CB, UL DAI is used for generating HARQ CB. * This feature is subject to separate UE capabilities for type-1, type-2, and type-3 codebooks. * RRC parameter(s) to configure the function of scheduling PDSCH after a UL DCI format and multiplexing associated HARQ on a PUSCH repetition except the first repetition are introduced in Rel-18. * Note: the number of PUSCH repetitions can be scheduled/configured by gNB. * Note: same principle of current specification which UL DAI in UL grant is applied to each PUSCH repetition is reused. * The timeline specified in TS 38.213 Clause 9.2.5 are satisfied, i.e. between the last PDSCH and PUCCH, between the last PDCCH among UL grant /DL grant(s) and the earliest PUCCH or PUSCH * Additional UE capabilities are introduced to support the following functions (UE will be configured by gNB to use the following features via RRC)   + ~~HARQ-ACK codebook size change on a PUCCH slot~~   + ~~PUCCH resource change on a PUCCH slot~~   + Support determining a PUCCH resource in a slot that starts in a same time in the slot as the PUCCH resource determined based on HARQ-ACK information associated with PDSCH reception(s) scheduled before a UL grant that schedules a PUSCH in that slot |   **Proposal 5 Further discuss the updates needed for the corresponding specifications.** |

# Discussion

## On condition for the codebook size

In [2], Ericsson discusses the impact of the condition for the codebook size change, copied below.

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| Definitely the restriction on the same codebook size is not motivated from network point of view, since the typical case of operation is that there are more DL opportunities to schedule before UL grant that after UL grant before start of repetition. Hence, this restriction makes the feature almost useless from network point of view.  On the other hand, it is not clear the how the restriction on same of different codebook size has any benefit and reduces UE’s complexity. Indeed, it forces the UE to adopt different logic and procedures for this case as compared to the normal UE procedures for codebook generation.  That in practice means that after any UL grant the UE has to execute the new logic/procedure.  And how does the new logic work?   * For example for Type-2 codebook, UE determines the size of codebook size based on detected PDSCHs and UL DAI. Then, UE needs to make a comparison and evaluate whether the generated codebook is valid or not based on its size. Considering the chance of DL miss-detection UE may assume error case in case of mis-match and after comparison. * Another example for Type-2 codebook is that the UE determines the size of codebook size based on detected PDSCHs and UL DAI and stops detecting PDSCHs when the size matched the size of codebook size before the UL grant, or the UE performs padding to match the size if needed.   The argument that the gNB should ensure the same codebook size, is not a reasonable argument due to DL miss-detection and contradicts with the whole principal on codebook generation.  The important factor is to follow the UL DAI for codebook generation before or after UL DAI.  Moreover, FG 55-4a/b/c include a note that the codebook size before and after UL DAI should be the same. However, they are considered as pre-requisite of the FG 55-4e where its description suggests completely the opposite.  Therefore, this restriction not only is technically wrong but also increases UE complexity and make the feature useless from network point of view.   1. The condition on same codebook size is technically incorrect. 2. The condition on same codebook size increases UE complexity. 3. The condition on same codebook size makes the feature useless to be enabled. 4. The important factor is following the UL DAI for codebook generation before or after UL DAI, and not requiring the same codebook size before or after UL DAI 5. The condition on same codebook size has caused contradictions in corresponding UE features descriptions. |

Regarding the above analysis and observations, Moderator has a different understanding.

On the motivation, in Moderator’s understanding, the motivation of the additional UE feature report is to provide more flexibility to enable the feature at least for less capable UEs. For example, if a UE does not support HARQ-ACK codebook size change due to implementation reasons, the UE cannot indicate to support FG 55-4a/4b/4c, in this case, network cannot schedule a DL grant after a UL grant. On the contrary, with the separate UE capability FG 55-4e, the less capable UEs can still support FG 55-4a/4b/4c without indicating to support FG 55-4e. During previous discussion, it was pointed out that in legacy the HARQ-ACK codebook size can be determined once the UL grant is received instead of waiting to a deadline determined based on the overlapping PUCCH/PUSCHs. Then, the UE can determine the REs for the UCI and UL data. If the HARQ-ACK codebook size does not change, the UE only needs to replace the HARQ-ACK information bits without re-determining the REs for the UCI and UL data and thus simplify UE implementation. It was also pointed out by companies that UCI multiplexing in a CG PUSCH also requires the UE to wait to monitoring DCI before a deadline determined by and the earliest symbol of the overlapping PUCCH/PUSCH, however, supporting CG PUSCH is an optional feature in legacy and may not be supported by all the UEs. In addition, same HARQ-ACK codebook size is a typical case for Type-1 and Type-3 HARQ-ACK codebook, enforcing UE to support HARQ-ACK codebook size change seems not necessary.

On the UE complexity, in Moderator’s understanding, the UE behaviour of generating a HARQ-ACK codebook is the same as legacy as stated in the agreement and it does not require the UE to make a comparison and evaluate whether the generated codebook is valid or not. On the other hand, it is gNB’s responsibility to ensure that the HARQ-ACK codebook size is not changed and the UE generates the HARQ-ACK codebook based on this assumption. For Type-2 HARQ-ACK codebook, even if there is DL DCI missing, it does not mean the UE determines a different HARQ-ACK codebook size. For example, gNB schedules 4 DL DCI and UL DAI indicates 4, if the UE receives at least one DL DCI, the HARQ-ACK codebook size would be determined as 4 assuming 1 TB case. Actually, the HARQ-ACK codebook size would not be an issue if the number of continuous DL DCIs is no larger than 4. The case of 4 or more continuous DL DCIs missing should be avoided by gNB implementation and usually is not considered for Type-2 HARQ-ACK codebook. For the 2nd Ericsson’s example, the UE does not need to stop detecting DCI since UE would not assume that gNB would schedule a DL DCI resulting in a different HARQ-ACK codebook size. If the last DL C-DAI/T-DAI does not equal to UL DAI, padding NACKs would be added which is also the same as legacy.

**Q1: What is your understanding regarding the UE behaviour if the UE does not indicate to support FG 55-4e (HARQ-ACK codebook size change) ?**

**Alt1: UE makes a comparison and evaluate whether the generated codebook is valid or not.**

**Alt2: UE assumes the network would ensure the HARQ-ACK codebook size would not be changed after receiving DL DCI coming after UL grant.**

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**Q2: Do you agree to remove the UE capability of indicating HARQ-ACK codebook size change?**

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## On condition for PUCCH resource change

In [1], Samsung discusses the impact of PUCCH resource change, copied below.

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| When a DL assignment comes after an UL grant for a UE, the UE determines the HARQ-ACK codebook and a PUCCH resource based on the HARQ-ACK codebook size and the PRI indication in the last DCI format for DL assignment before the UL grant. After that, the UE multiplexes the HARQ-ACK in a PUSCH overlapping with the PUCCH, if any. If PUCCH time domain resource is different from the PUCCH that UE determines before the UL grant, UE may multiplex the HARQ-ACK in another PUSCH. As a result, it would take additional time for the UE to re-determine the PUSCH and the REs for both the HARQ-ACK and the data in the PUSCH.  An example is given in Figure 1 for illustration. UE first determines to multiplex HARQ-ACK in PUCCH#1 before receiving the UL DCI#1 and UL DCI#2, and then UE determines to multiplex HARQ-ACK in PUSCH#1 after receiving the UL DCI#1 and UL DCI#2. If the UE receives DL DCI 2a as shown in case a), UE needs to re-determine the PUSCH for multiplexing based on the PUCCH resource indicated by DL DCI 2a. On the other hand, if UE receives DL DCI 2b as shown in case b) indicating the same PUCCH time domain resource as PUCCH#1, the UE does not need to re-determine the PUSCH for HARQ-ACK multiplexing. The additional timeline is not required for this case. Therefore, the additional UE capability is not needed either.  **Observation 1**: If the time domain of the PUCCH resource does not change before and after the UL grant, a UE does not need additional timeline to determine the PUSCH for HARQ-ACK multiplexing.    case a) case b)  Figure 1  If a UE indicates the capability of supporting PUCCH resource change in a PUCCH slot, it is possible that the final PUCCH after receiving the last DL grant does not overlap with the PUSCH repetition. An example in given in Figure 2 for illustration. The UE first determines a PUCCH#1 with HARQ-ACK overlapping with a PUSCH repetition in a slot, the HARQ-ACK would be multiplexed in the PUSCH repetition and if the UE does not receive any DL grant coming after the UL grant as in legacy. However, if a Rel-18 UE receives a DCI format at a later time indicating HARQ-ACK in the same slot, the UE should perform HARQ-ACK overriding and re-determine a PUCCH resource for the multiplexed HARQ-ACK information bits. If the later determined PUCCH#2 does not overlap with the PUSCH, the UE should not multiplex HARQ-ACK in the PUSCH, therefore, it should be ensured that the UE has enough time to cancel the multiplexing of HARQ-ACK in the PUSCH, i.e., the time gap between T0 (the ending of PDCCH with the DL grant) and T1 (the starting of the PUSCH repetition) should be no less than a threshold. The current spec only defines the timeline requirement for the case where PUCCH#2 overlaps with the PUSCH repetition. The timeline for this case should also be defined, for example, the multiplexing timeline defined in 9.2.5 can apply here assuming PUCCH#2 overlaps with the PUSCH repetition #2.    Figure 2  **Observation 2**: If the DL grant coming after the UL grant indicating a PUCCH transmission not overlapping with the PUSCH repetition and if the PDCCH reception that includes the DL grant is not earlier than a predefined timeline from the beginning of the PUSCH repetition, a UE does not have enough processing time to cancel the multiplexing of HARQ-ACK in the PUSCH repetition. |

In [2], Ericsson also discusses the impact of the condition for the PUCCH resource change, copied below.

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| Another condition for the UE features in the agreement above is the condition on the same PUCCH resource. Similar to the previous discussion, it is not clear the how the restriction on PUCCH resource has any benefit and reduces UE’s complexity. Indeed, it forces the UE to adopt different logic and procedures for this case as compared to the normal UE procedures for PUCCH resource determination.  Per normal procedures, based on the codebook size and indicated PRI, the UE determines the PUCCH resource for carrying HARQ-ACK. That in practice means that after any UL grant the UE has to execute the new logic/procedure.  And how does the new logic work?   * Does the UE determine PUCCH resources before and after and make comparison? What if there is a mismatch at the outcome of comparison due to DL misdetection?   When it comes to PUCCH resource, there is one element that can indeed reduce the UE complexity, and that skipping multiplexing timeline calculation as the following:  If in a PUCCH slot that UE has determined a PUCCH resource for HARQ-ACK information corresponding to the PDSCHs before UL grant and UE determines a PUCCH resource for HARQ-ACK information corresponding to the PDSCHs after UL grant, the UE can skip new timeline calculation if these two PUCCH resources start at the same time in the PUCCH slot.  We believe that is an important aspect that simplifies UE’s complexity and worth to be indicated as capability.   1. The condition on same PUCCH resource increases UE complexity. 2. Reusing multiplexing timeline for a PUCCH slot with HARQ-ACK before UL grant and after UL grant reduces UE complexity. |

In both contributions, the restriction of PUCCH resource change in frequency domain is suggested to be removed. The issue was also discussed in RAN1#114bis meeting and a majority companies are fine with removing the restriction [3].

**Q3: Do you agree to remove the additional UE capability of indicating PUCCH resource change in frequency domain?**

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| QC | If we assume the timeline considerations in 9.2.3 are adhered to, we wonder if any of these issues arise. We seem to have missed it in TEI agreement. May be adding it explicitly might resolve some of the above issues.  We want to be a bit cautious with the capabilities here as we don’t want to inadvertently agree to an alternate timeline that does not line up with legacy behavior (especially in the CG-PUSCH context) |
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Ericsson points out that the restriction on PUCCH resource change forces the UE to adopt different logic and procedures that UE needs to make a comparison on the PUCCH resources determined before and after UL grant, however, in Moderator’s understanding, such comparison is not needed for UE and the UE behaviour is the same as legacy for PUCCH resource determination. Instead, it should be ensured by network that the PUCCH resource does not change if a UE does not indicate the additional UE capability of supporting PUCCH resource change.

**Q4: What is your understanding regarding the UE behaviour if the UE does not indicate to support FG 55-4d (PUCCH resource change) ?**

**Alt1: UE makes a comparison on the PUCCH resources determined before and after UL grant.**

**Alt2: UE assumes the network would ensure the PUCCH resource would not be changed after receiving DL DCI coming after UL grant.**

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The timeline conditions are discussed in both contributions, Samsung pointed out a new timeline issue as shown in Figure 2 [1].

**Q5: Do you agree with the following observation made by Samsung?**

**Observation 2**: If the DL grant coming after the UL grant indicating a PUCCH transmission not overlapping with the PUSCH repetition and if the PDCCH reception that includes the DL grant is not earlier than a predefined timeline from the beginning of the PUSCH repetition, a UE does not have enough processing time to cancel the multiplexing of HARQ-ACK in the PUSCH repetition.

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To resolve the new timeline issue, Samsung proposes that the PDCCH carrying DL grant should satisfy the UCI multiplexing timeline regardless of the later determined PUCCH overlaps with the PUSCH or not.

**Q6: Do you agree that the PDCCH carrying DL grant should satisfy the UCI multiplexing timeline regardless of the later determined PUCCH resource overlaps with the PUSCH repetition or not?**

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Ericsson points out that the UE can skip new timeline calculation if PUCCH resources start at the same time in the PUCCH slot determined before and after the UL grant and propose it as a new UE capability. However, in moderator’s understanding, the separate UE capability is for advanced UEs, the proposed UE capability seems for less capable UEs. If Moderator’s understanding is correct, this should be baseline, supporting different starting PUCCH resource should be an additional UE capability. In addition, the new UE capability still requires a UE to re-determine the PUSCH selection as shown in Figure 1. Before detecting DCI#2, the HARQ-ACK is multiplexed in PUSCH#1 REP#2 of CC2 but after detecting DCI#2, the HARQ-ACK is multiplexed in PUSCH#2 REP#2 of CC1 with the smaller serving cell index. On the other hand, the restriction on the PUCCH resource change in time domain can avoid re-determining the PUSCH for HARQ-ACK multiplexing. There are 3 alternatives for the additional UE capability regarding PUCCH.

Alt 1: Support determining a PUCCH resource in a slot that starts in a same time in the slot as the PUCCH resource determined based on HARQ-ACK information before a UL grant that schedules a PUSCH in that slot. (Ericsson’s proposal)

Alt 2: Support determining a PUCCH resource in a slot that starts in a different time in the slot as the PUCCH resource determined based on HARQ-ACK information scheduled before a UL grant that schedules a PUSCH in that slot. (Moderator’s update based on Ericsson’s proposal)

Alt 3: PUCCH time domain resource change in a PUCCH slot. (Samsung’s proposal)

For Alt 1, it is not clear to the Moderator what is the default capability if a UE does not report the additional capability, @Ericsson, please help clarify.

In moderator’s understanding, both Alt 2 and Alt 3 can avoid the new timeline checking and the difference is that alt 3 can avoid PUSCH re-determination but Alt 2 cannot avoid it.

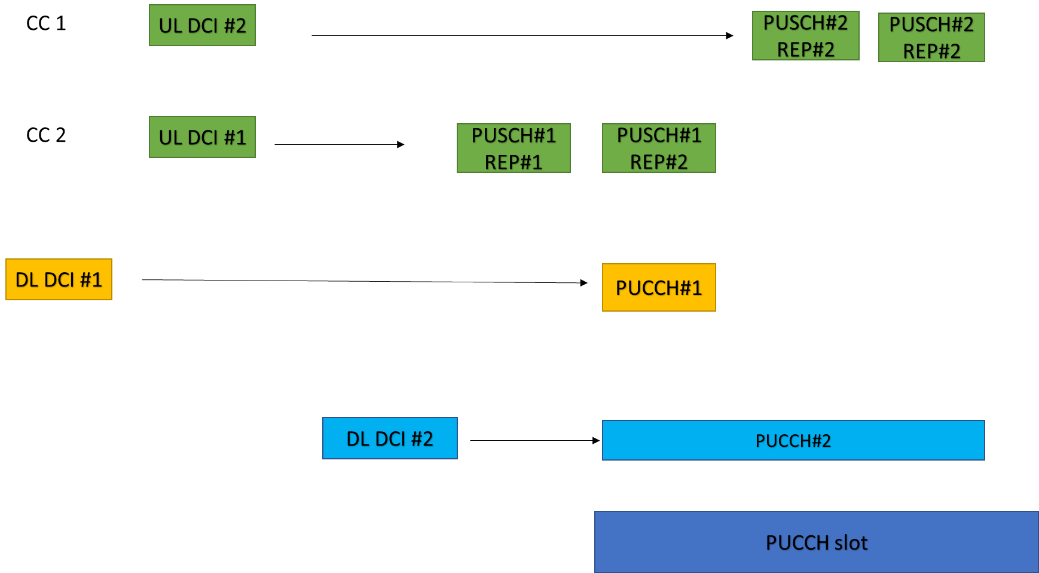


Figure 1

**Q7: What is your preference on the additional UE capability regarding PUCCH resource?**

**Alt 1: Support determining a PUCCH resource in a slot that starts in a same time in the slot as the PUCCH resource determined based on HARQ-ACK information before a UL grant that schedules a PUSCH in that slot.**

**Alt 2: Support determining a PUCCH resource in a slot that starts in a different time in the slot as the PUCCH resource determined based on HARQ-ACK information scheduled before a UL grant that schedules a PUSCH in that slot.**

**Alt 3: PUCCH time domain resource change in a PUCCH slot.**

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## DL DCI without scheduling a PDSCH

Samsung points out that the previous discussion only considers the DL grant scheduling a PDSCH, for a DCI format indicating HARQ-ACK information without scheduling a PDSCH, there is no essential difference and the same restriction can also be relaxed to provide the flexibility of network scheduling.

**Q8: Do you see any difference between a DL DCI scheduling a PDSCH and a DL DCI not scheduling a PDSCH indicating HARQ-ACK in a PUCCH for the Rel-18 TEI case of UCI multiplexing in a PUSCH repetition?**

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**Q9: Do you agree to extend the relaxation to a DL DCI not scheduling a PDSCH indicating HARQ-ACK in a PUCCH for the Rel-18 TEI case of UCI multiplexing in a PUSCH repetition, i.e., the following update for the main bullet of the previous agreement?**

**If UCI multiplexing of different priorities is not enabled, the restriction on DL DCI format indicating HARQ-ACK information with/without scheduling PDSCH after UL grant is removed for the case of PUSCH with repetitions except the first repetition**

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# Conclusion

TBD

# Reference

[1] R1-2311882     Remaining issue for HARQ-ACK multiplexing on PUSCH        Samsung

[2] R1-2312245     Discussion on HARQ-ACK multiplexing on PUSCH TEI  Ericsson

[3] R1-2310513    Summary of discussion on multiplexing HARQ-ACK in a PUSCH Moderator (Samsung)