3GPP TSG RAN1#61b **R1-104216**
Dresden, Germany
28 June- 2 July, 2010

Agenda item: **6.4.2**
Source: **Motorola**
Title: **UCI Multiplexing on PUSCH in UL-MIMO Transmissions**
Document for: **Discussion/Decision**

1. Introduction

At RAN1#61 the multiplexing of uplink control information on PUSCH for the case of uplink spatial multiplexing was discussed and the following conclusions agreed: HARQ-ACK and RI:

  - Replicated across all layers of both CWs
  - TDM multiplexed with data such that UCI symbols are time-aligned across all layers
    - FFS: How to determine the number of UCI symbols on each CW and each layer
- CQI/PMI: transmitted only on 1 codeword
  - Reuse Rel-8 multiplexing and channel interleaving mechanisms
    - Extension: The input to data-control multiplexing $q_0, q_1, q_2, q_3, \ldots, q_{Q_{CQI}-1}$, $f_0, f_1, f_2, f_3, \ldots, f_{G-1}$ } is grouped into column vectors $\underline{g}_0, \underline{g}_1, \underline{g}_2, \underline{g}_3, \ldots, \underline{g}_{H'-1}$ of length Q_m*L
      - L (1 or 2) is the number of layers the CW is mapped onto
      - Enable time (RE) alignment across 2 layers for L=2
  - UCI symbol-level layer mapping: same as (treated as a part of) data
  - FFS: Mechanism for CW selection

The requirement of a replication stage in the processing of HARQ-ACK and RI symbols ensures both symbols are transmitted with full transmit power while at the same time reducing sensitivity to precoder selection [1]. The time alignment of UCI symbols across layers is motivated by the desire to reduce coupling between received data and control symbols thereby simplifying implementation. With these constraints in mind, this contribution analyzes the default UCI mapping given above consisting of replicating UCI across layers and transmitting time-aligned UCI symbols in a TDM fashion. This approach is then compared with an alternative transmit diversity scheme based on Alamouti encoding. The contribution also addresses the problem of determining the number of UCI symbols to be allocated to HARQ-ACK and rank indication [2]. The assumptions on HARQ-ACK and rank indication symbol mapping are first reviewed followed by a discussion of three cases corresponding to different codeword/layer combinations. Proposals are given for all case. The more interesting case of two codewords is discussed in depth and a proposal based on extending the Release 8 expression is derived. A similar proposal is given in [3]. An alternative proposal is suggested in [4]. This contribution is a revision of R1-103916.

2. Rank and HARQ-ACK Symbol Mapping on PUSCH

The block diagram in Figure 1 illustrates mapping of HARQ-ACK and rank indication with the working assumption of symbol replication shown occurring at the output of the channel coder and prior to data/control multiplexing and interleaving. For both HARQ-ACK and rank indication, codeword i 's replication stage repeats channel coded bits according to ν_i, the number of layers on codeword i, to give $Q_{i,RI}$ and $Q_{i,ACK}$ coded bits of rank indication and HARQ-ACK information respectively on codeword i.

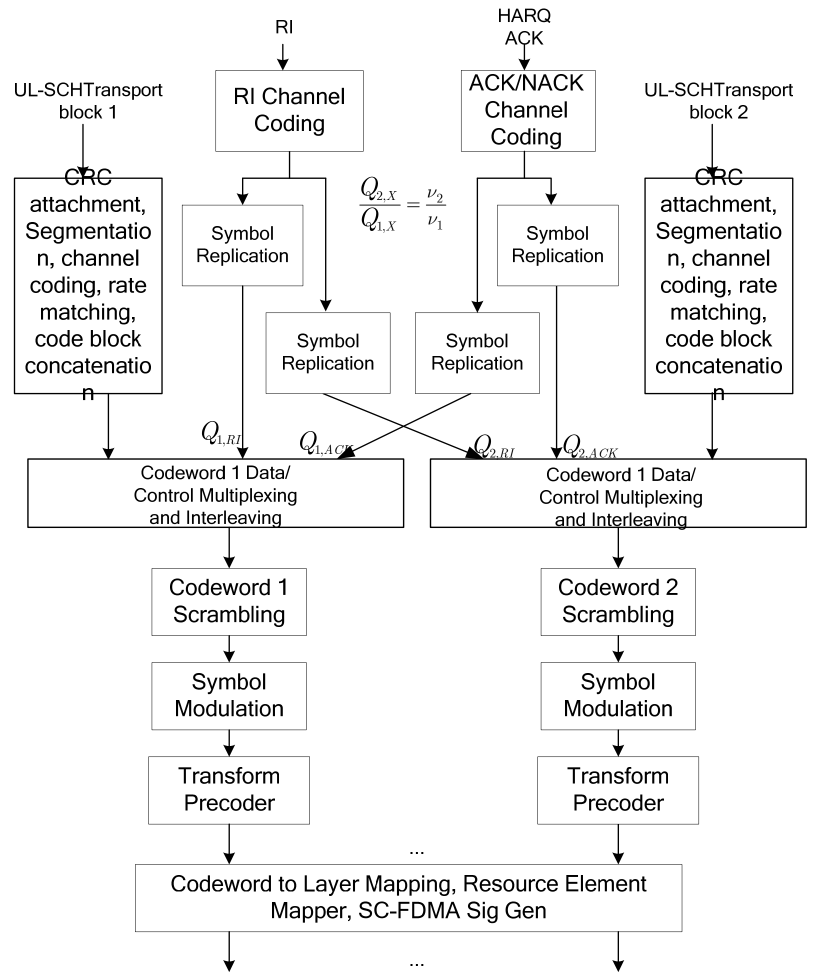

RI
HARQ ACK
UL-SCHTransport block 1
RI Channel Coding
ACK/NACK Channel Coding
UL-SCHTransport block 2
CRC attachment, Segmentation, channel coding, rate matching, code block concatenation
$\frac{Q_{2,X}}{Q_{1,X}} = \frac{\nu_2}{\nu_1}$
Symbol Replication
Symbol Replication
Symbol Replication
Symbol Replication
CRC attachment, Segmentation, channel coding, rate matching, code block concatenation
$Q_{1,RI}$
$Q_{1,ACK}$
$Q_{2,RI}$
$Q_{2,ACK}$
Codeword 1 Data/ Control Multiplexing and Interleaving
Codeword 1 Data/ Control Multiplexing and Interleaving
Codeword 1 Scrambling
Codeword 2 Scrambling
Symbol Modulation
Symbol Modulation
Transform Precoder
Transform Precoder
...
Codeword to Layer Mapping, Resource Element Mapper, SC-FDMA Sig Gen
...

Figure 1: HARQ ACK and Rank Indication Mapping on PUSCH. Note: CQI not shown.

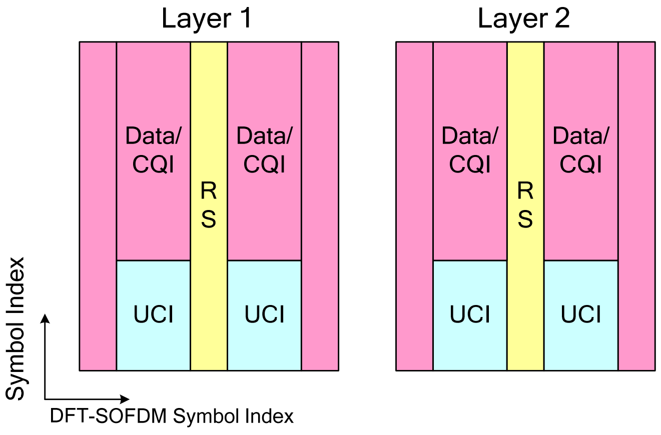


Figure 2: Time Alignment of UCI between layers. Due to the properties of SC-OFDM , the vertical axis (Symbol Index) corresponds to time.

The multiplexing and interleaving block time aligns UCI symbols across layers so that control and data symbols are not sent at the same time on different layers as shown in Figure 2. The details of how this is to be performed, i.e. how the UCI symbols are to be arranged in the blue region of Figure 2 were discussed in [5] where it was suggested to reuse the multiplexing scheme of Release 8 and employ layer-specific scrambling of the replicated UCI symbols. This approach was not adopted at RAN1#61. Rather, only UCI replication across layers was agreed. While symbol replication has the advantage of being simple to specify and utilizes full transmission power at each of the PAs, it may not provide transmission diversity between layers. A possible alternative approach based on rank 2 diversity transmission is investigated in Figure 3 for the case of two layer PUSCH transmission.

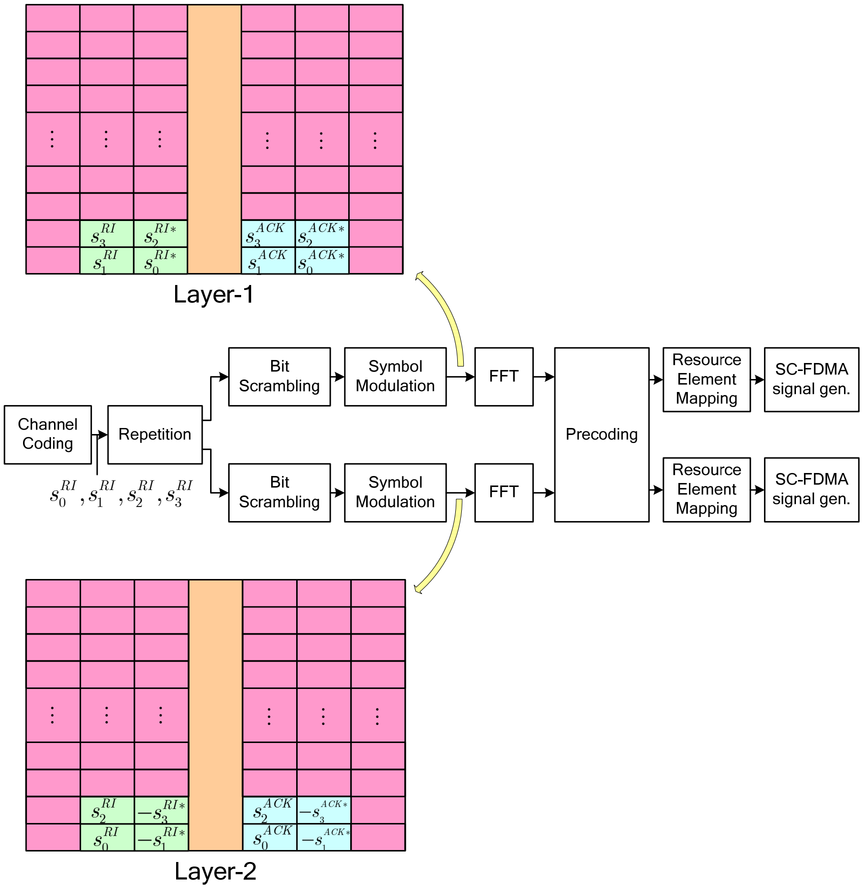
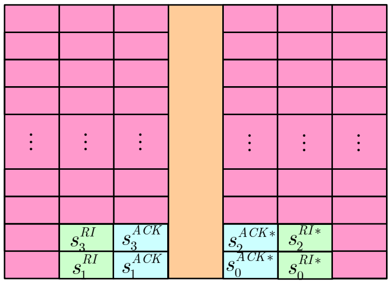
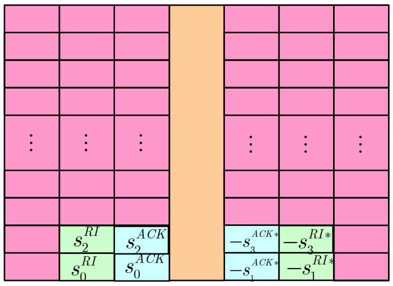


Figure 3: Proposed HARQ ACK and RI symbol mapping. The block diagram shows only RI processing. Similar processing is performed for HARQ ACK.

This is like applying Alamouti scheme on time domain UCI symbols. Prior to DFT coding, a pair of symbols is encoded with the usual Alamouti encoding rule across a pair of SC-OFDM symbols and a pair of layers. Like the symbol replication scheme described above, the proposed approach multiplexes UCI symbols in time and achieves full PA power utilization across all antennas. HARQ-ACK and rank indication are shown multiplexed to different halves of the slot with transmissions occurring on adjacent SC-OFDM symbols. This was done to minimize the changes in the channel between transmissions Alternatively as shown in Figure 4, HARQ ACK could be multiplexed to the SC-OFDM symbols on either side of the DMRS and rank indication multiplexed +/- 2 SC-OFDM symbols on either side of the DMRS as in Release 8. Rank indication performance in high Doppler channels may suffer in this configuration due to the channel changing across four SC-OFDM symbols. The mapping in Figure 3 is therefore preferred.



Layer-1



Layer-2

Figure 4: Alternative symbol positions for RI and HARQ ACK mapping. Transmissions are separated by two and four SC-OFDM symbols for RI and HARQ ACK respectively, which may impact performance under high speed. However this mapping reuses the symbol mapping in Release 8.

Due to the multiplexed UCI and data transmission, the Alamouti-encoded symbols and data symbols still need the receiver to separate the two layers as in PUSCH MIMO. Then the IDFT operation will restore the QAM symbols. The process is like a space-time equalizer. For example, if two coded UCI symbols s_1 and s_2 are transmitted on two layers of the first SC-OFDM symbol, then the equalizer outputs, y_1 and y_2, after despreading with the IFFT can be written

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} h_{11} & * \\ * & h_{22} \end{bmatrix} \begin{bmatrix} s_1 \\ s_2 \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \end{bmatrix}$$

where n_1 and n_2 represent additive interference and noise. Note that in general n_1 and n_2 could be correlated due to the equalization being performed in the spatial domain. The diagonal elements in the above reflect the equivalent post-equalization channels, and one may ignore interlayer interference if it is insignificant relative to additive noise. The channel matrix at the second SC-OFDM symbol time is, by assumption, the same if we assume the same channel during the second SC-OFDM time period and therefore the second set of observations y_1' and y_2' are given by

$$\begin{bmatrix} y_1' \\ y_2' \end{bmatrix} = \begin{bmatrix} h_{11} & * \\ * & h_{22} \end{bmatrix} \begin{bmatrix} -s_2^* \\ s_1^* \end{bmatrix} + \begin{bmatrix} n_1' \\ n_2' \end{bmatrix}.$$

The observations y_1, y_2, y_1', and y_2' can be combined to give an SNR per symbol of $SNR = \left(\left|h_{11}\right|^2 + \left|h_{22}\right|^2\right) / \sigma_n^2$ since the noise in different SC-OFDM symbols is uncorrelated..

While it is true that the symbol replication approach as illustrated in Figure 5 can also directly use the equalization outputs, the same SNR will not generally be obtained. With the symbol replication approach, the signal model above is replaced by

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} h_{11} & * \\ * & h_{22} \end{bmatrix} \begin{bmatrix} 1 \\ 1 \end{bmatrix} s + \begin{bmatrix} n_1 \\ n_2 \end{bmatrix}$$

where s is the UCI symbol. One may expect the SNR to be the same with $SNR = \left(|h_{11}|^2 + |h_{22}|^2\right) / \sigma_n^2$ where σ_n^2 is the variance of n_1 and n_2. However, d*ue to the possibility of* n_1 *and* n_2 *being correlated however, there could be performance difference.* The performance difference of the symbol replication approach and the proposed rank 2 scheme will be discussed further below.

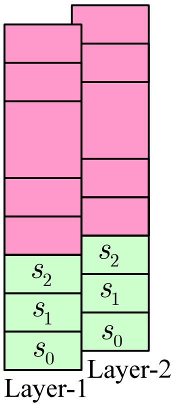
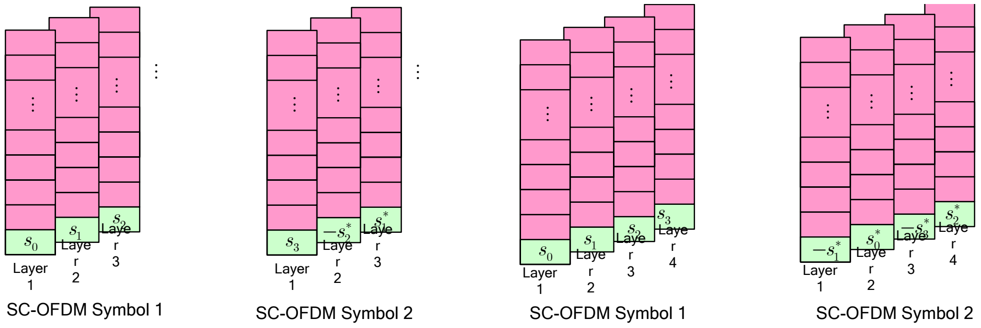


Figure 5: Replicated transmission of time domain UCI symbols

By using two sets of two layers, the two layer mapping of Figure 3 can be extended to four layers. For the three layer case, two UCI symbols can be mapped to the first layer of both SC-OFDM symbols while layers two and three can again use the two layer approach of Figure 3. Note that with the agreed upon rank 3 codebook the first layer transmits from two antennas and therefore has twice the power of the other layers. The proposed mappings for three and four layers are shown in Figure 6.



a) 3 Layers

b) 4 Layers

Figure 6: Proposed Mapping for a) 3 layers and b) 4 layers

2.1. Simulated Performance of Symbol Replication and Transmission Diversity Schemes

Two UCI mapping schemes were evaluated by link simulation in a 2 X 2, two layer configuration. In the simulations a two bit UCI payload was channel coded according to Sec. 5.2.2.6 of 36.212 v0.87 assuming $2Q'$ channel coded bits. The quantity Q' is the total number of UCI modulation symbols on all layers and can be varied to obtain different levels of UCI message error rate. The resulting channel coded bits were converted to modulation symbols and then mapped according to one of two schemes. The first was the rank 2 diversity scheme shown in Figure 3 and referred to as '*Alamouti*' while the second consisted of replicating coded UCI symbols in a time-aligned fashion across layers as shown in Figure 5. This second approach, referred to as '*Rank1*', is kind of like precoding the time-domain UCI symbols with a fixed precoding vector of $\begin{bmatrix}1 & 1\end{bmatrix}$. The remaining symbols were filled with random QPSK symbols to emulate the presence of multiplexed data. FFT precoding was applied to each layer and each layer transmitted on its corresponding antenna since for 2 Tx, the only rank 2 precoder to be used for uplink spatial multiplexing is the identity matrix. In each of the cases, the layer outputs of a frequency-domain equalizer were combined with weights calculated based only on the diagonal elements of the effective channel matrix (defined as the concatenation of the physical channel between transmit and receive antennas and the equalization filter) and the noise variance of the layer outputs. Additional assumptions are given in the Appendix.

The 2 bit UCI message error rate is plotted vs. transmitted SNR or I_{or} / I_{oc} for flat and TU6 channels and $Q' = 4$ and $Q' = 6$ in Figure 7 and Figure 8 respectively. From the plots it is clear that simply transmitting the replicated UCI symbols on each layer performs very poorly, especially in flat channels (or with narrow bandwidth UL allocation) where at least a 5 dB loss is observed relative to the diversity transmission scheme. This is expected since the transmission is effectively over a single antenna port and therefore no transmission diversity is possible. In the TU6 channel on the other hand, when abundant frequency diversity is available since the simulation assumes the transmission bandwidth of $N_{fft} = 512$ subcarriers, the relative gain is smaller, on the order of 2 dB at the target error rate of $10^{-4.}$ for both four symbol, $Q' = 4$, and six symbol cases, $Q' = 6$.

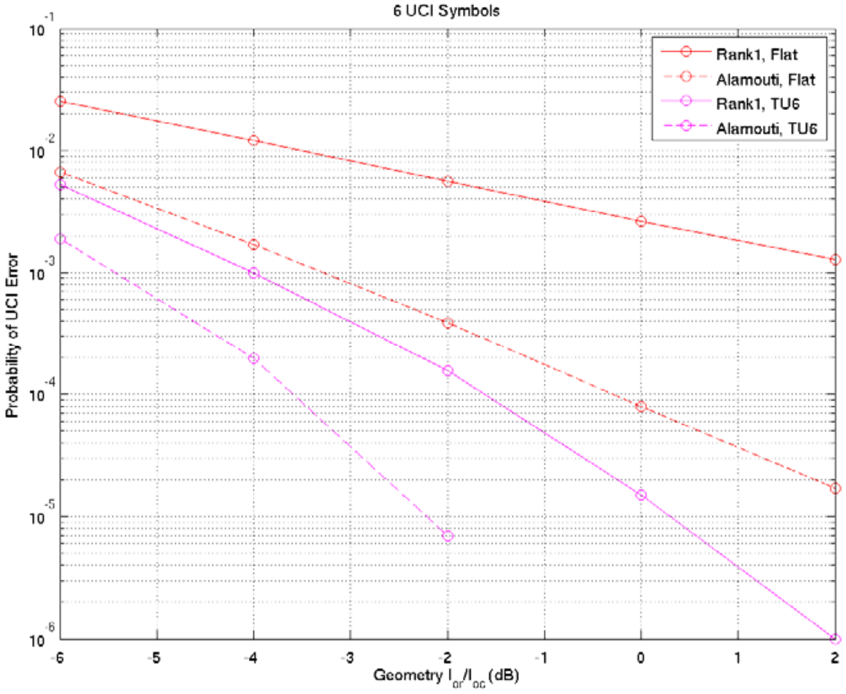


Figure 7: Message error rate (2 bits) for $Q' = 4$ UCI symbols in flat and TU6 channels for the two mapping schemes.

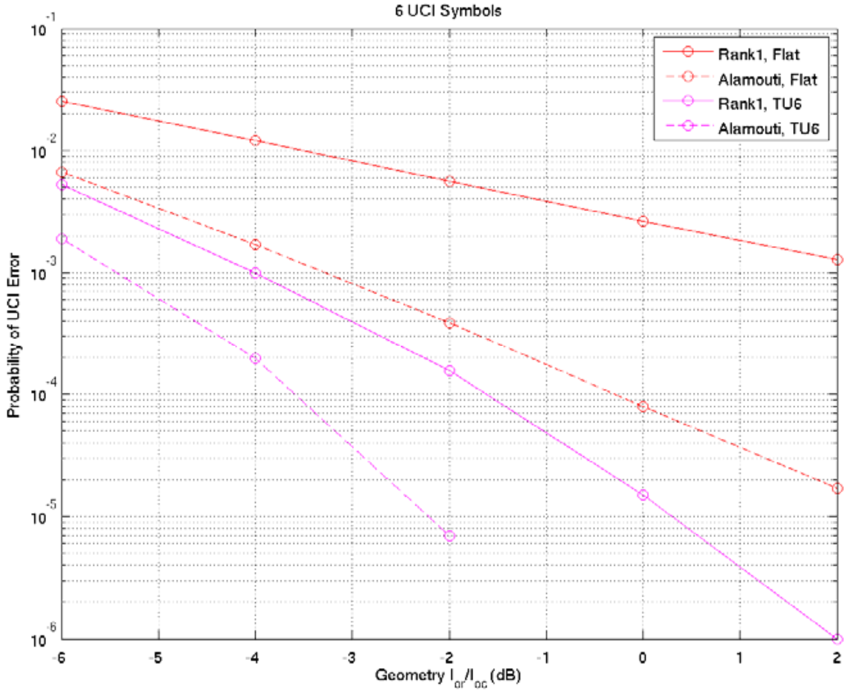


Figure 8: Message error rate (2 bits) for $Q' = 6$ UCI symbols in flat and TU6 channels for the two mapping schemes.

Based on performance exhibited by the transmission diversity approach, we recommend:

Proposal: Investigate more optimal mapping of UCI symbols instead of simple replication, such as the scheme of Figure 3.

3. Control Symbol Allocation for Multi-Antenna Transmission

For the purposes of determining the number of UCI symbols with multilayer transmission, there are three cases of interest: 1) Single codeword and single layer transmission 2) Single codeword and multiple layers and 3) Two codewords and therefore multiple layers. Each case is discussed below.

3.1.1. Single Codeword and Single Layer Transmission

The first case can reuse the expression for UCI symbols in Release 8 without modification:

Proposal: Reuse the Release 8 expression for the number of HARQ-ACK and rank indication symbols for single codeword single layer transmission.

3.1.2. Single Codeword and Multiple Layers

The second case occurs during a non-adaptive transmission of transport block which was originally transmitted along with another transport block on four layers. If the other transport block is correctly decoded after the first transmission, then according to the Release 8 downlink layer mapping rules which have been carried over multi-antenna transmission on the uplink, a single transport block two layer retransmission may be performed. While this case differs from single antenna Release 8 transmission in that multiple layers are involved, the same expression for number of HARQ-ACK and rank indication symbols can be reused with a UL spatial multiplexing specific rank 1 power offset factor $\beta_{1,offset}^{SM}$. A new offset is needed because the receiver performance in terms of received symbol SNR will not in general be the same for single and multiple layer receivers.

Proposal: Reuse the Release 8 expression for the number of HARQ-ACK and rank indication symbols with a power offset factor specific to single codeword multilayer transmission.

3.1.3. Two Codeword Case

The last case of multiple codewords is not as clear. Several observation can be made however. First, the reliability of estimated UCI coded bits fed to the decoder is a function of the symbol SNRs on all layers and therefore both codewords' code rate and modulation order give information on the reliability of received control symbols. The associated fields in the uplink grant corresponding to both codewords should therefore be used to determine the number of HARQ-ACK and rank indication symbols.

Observation: The number of HARQ-ACK and rank indication symbols should be a function of both codewords' resource allocation and MCS fields.

In order to maintain consistency between single and multiple codeword operation, it is desirable to try to extend the methodology used in Release 8 to the multiple codeword case. This allows the same interpretation to the expression for both cases thereby simplifying the design process. The derivation of the Release 8 expression for number of control symbols and how it can be extended to the multiple codeword case will be discussed below.

Observation: Extending the Release 8 expression for the number of UCI symbols to the multiple codeword case should be used as a baseline unless there is a compelling performance advantage to do otherwise

Although different eNB manufacturers will no doubt implement different receivers for UL MIMO, the performance of a reasonable receiver in a channel where the second codeword's layers have negligibly small gain (and therefore a TBS of near zero) should approach the performance with a single codeword case-either case 1 or case 2 above depending on the number of layers used for the dominant codeword. Since the expressions for the number of symbols in these cases was proposed to be the same as Release 8 with a possibly different offset factor, it is reasonable to assume that the expression for the number of UCI symbols in the two codeword case will approach the Release 8 expression (to within a scale factor) as the one of the codeword's TB size goes to zero:

Observation: The number of UCI symbols required in the multi-codeword case should approach the number in Release 8 as the TB size indicated in the uplink approaches zero.

3.2. Extending the Release 8 Approach to Multiple Codewords

This section proposes an expression for the number of HARQ-ACK and rank indication symbols to be used with multiple codeword transmission. The proposal satisfies the three observations above: 1) It is a direct extension of the Release 8 expression 2) Is a function of both TBSs, and 3) It reduces to the Release 8 equation when one of the TBS goes to zero. The derivation of the Release 8 expression is given first to help motivate the multi-codeword case.

Release 8 Derivation of the Number of UCI Symbols

The approach taken in Release 8 was to allocate Q' control symbols such that the UCI energy-per-information bit, E_b^{UCI} was proportional to the energy-per information bit of the symbols corresponding to UL-SCH, E_b, with the proportionality constant being the higher-layer signaled parameter β_{offset}^{PUSCH}, i.e. $E_b^{UCI} = \beta_{offset}^{PUSCH} E_b$. With O bits of UCI, the total energy received in all UCI symbols is then

$$\begin{aligned} Received\ UCI\ Energy &= O \cdot E_b^{UCI} = Q' \cdot E_S \\ &= Q' \cdot E_b \cdot \left(code\, rate\right)_{UL\_SCH} \end{aligned}$$

where E_S^{rcvd} is the received energy per symbol which is assumed to be the same for a data or UCI symbol. Solving the above for Q', limiting the number of UCI symbols to the symbols available in 4 SC-OFDM symbols, and using the approximation,

$$\left(code\, rate\right)_{UL\_SCH} = \frac{\sum_{r=0}^{C-1} K_r}{M_{sc}^{PUSCH-initial} \cdot N_{symb}^{PUSCH-initial}}$$

where

- $M_{\text{sc}}^{\text{PUSCH}}$ is the scheduled bandwidth for PUSCH transmission in the current sub-frame for the transport block, expressed as a number of subcarriers,
- $N_{\text{symb}}^{\text{PUSCH-initial}}$ is the number of SC-FDMA symbols per subframe for initial PUSCH, transmission for the same transport block,
- The number of code blocks is C with sizes $K_1, \cdots, K_C$,
- β_{offset}^{PUSCH} is a higher layered signaled offset parameter.

gives the result in [6]:

$$Q' = \min\left(\left\lceil \frac{O \cdot M_{sc}^{PUSCH-initial} \cdot N_{symb}^{PUSCH-initial} \cdot \beta_{offset}^{PUSCH}}{\sum_{r=0}^{C-1} K_r} \right\rceil, 4 \cdot M_{sc}^{PUSCH} \right)$$

The number of uplink resources is seen to nominally be inversely proportional to the codeword's spectral efficiency.

Extension to Multiple Codewords

The method of determining the number of control symbols described above can easily be extended to multilayer transmission. Assume that codeword i contains Q_i' control symbols distributed among ν_i layers with each symbol having an average received symbol energy of $E_{S,i}$. The received UCI energy is then

$$\begin{aligned} Received\ UCI\ Energy = O \cdot E_b^{UCI} &= Q_1' \cdot E_S^1 + Q_2' \cdot E_S^2 \\ &= Q_1' \cdot E_b \cdot \left(cw\,1\,code\,rate\right)_{UL\_SCH} + Q_2' \cdot E_b \cdot \left(cw\,2\,code\,rate\right)_{UL\_SCH} \\ &= \frac{E_b}{M_{sc}^{PUSCH-initial} \cdot N_{symb}^{PUSCH-initial}} \left(\frac{Q_1'}{\nu_1} \sum_{r=0}^{C_1-1} K_{r,1} + \frac{Q_2'}{\nu_2} \sum_{r=0}^{C_2-1} K_{r,2} \right) \end{aligned}$$

Because the UCI is time-aligned across layers, the number of UCI symbols mapped to the codeword 2's layer(s) is ν_2 / ν_1 times the number of UCI symbols mapped to codeword 1's layers and therefore $Q_1' / \nu_1 = Q_2' / \nu_2$ which, when substituted into the above equation, gives the proposed expression:

$$Q_i' = \min\left(\left\lceil \frac{O \cdot \nu_i \cdot M_{sc}^{PUSCH-initial} \cdot N_{symb}^{PUSCH-initial} \cdot \beta_{offset}^{SM,PUSCH}}{\sum_{r=0}^{C_1-1} K_{r,1} + \sum_{r=0}^{C_2-1} K_{r,2}} \right\rceil, \ 4 \cdot \nu_i \cdot M_{sc}^{PUSCH} \right). \qquad (1)$$

Several Observations.

- In the multi-codeword case, the number of UCI symbols is inversely proportional to the average per-layer spectral efficiency.
- A new offset factor higher-layer signaled offset $\beta_{offset}^{SM,PUSCH}$ has been assumed.
- The number of symbols Q_i' is defined on a per-codeword basis and not a per-layer basis and this accounts for the number of layers, ν_i, appearing in the numerator.
- When one codeword's size approaches zero (say codeword 2) and codeword 1 has $\nu_1 = 1$ layer, the expression reduced to the Release 8 equation.

Proposal: The number of symbols for either HARQ-ACK or rank indication be given by (1) ***where*** $\beta_{offset}^{SM,PUSCH}$ ***is a higher layer signaled parameter.***

4. Conclusions

This contribution addressed two remaining aspects of transmission of UCI on PUSCH. First, three schemes for mapping of UCI symbols were evaluated by simulation. Transmitting replicated and time-aligned symbols across multiple layers was found to have particularly poor performance in flat channels compared with a proposed transmission diversity scheme which maps symbols across layers based on conventionial Alamouti encoding. The latter method was found to offer the best performance overall with little to no additional complexity at either the UE or eNB.

Proposal: Investigate more optimal mapping of UCI symbols instead of simple replication, such as the scheme of Figure 3.

The contribution also derived expressions for the number of symbols to be used for either HARQ-ACK or rank indication when multi-transmit antennas are used on the uplink. Three cases were discussed : 1) Single codeword and single layer transmission 2) Single codeword and multiple layers and 3) Two codewords and therefore multiple layers. Proposals based on the Release 8 expressions were given for each case.

Proposal (Single Codeword and Single Layer): Reuse the Release 8 expression for the number of HARQ-ACK and rank indication symbols for single codeword single layer transmission.

Proposal (Single Codeword and Multiple Layers): Reuse the Release 8 expression for the number of HARQ-ACK and rank indication symbols with a power offset factor specific to single codeword multilayer transmission.

Proposal (Multiple Codewords): The number of symbols for either HARQ-ACK or rank indication on codeword i ***is given by***

$$Q_i' = \min\left(\left\lceil \frac{O \cdot \nu_i \cdot M_{sc}^{PUSCH-initial} \cdot N_{symb}^{PUSCH-initial} \cdot \beta_{offset}^{SM,PUSCH}}{\sum_{r=0}^{C_1-1} K_{r,1} + \sum_{r=0}^{C_2-1} K_{r,2}} \right\rceil, 4 \cdot \nu_i \cdot M_{sc}^{PUSCH}\right).$$

5. Simulation Assumptions

System bandwidth	10 MHz
Data transmission BW	512 subcarriers
Slot format	Normal CP (7 symbols per slot)
Channel model	TU 6 and Flat Channel

UE Antenna Imbalance	0 dB
Antenna configuration	2 x 2 Tx Correlation =0 Rx Correlation = 0
Channel coding	Release 8 Channel Coding according to Sec. 5.2.2.6 of 36.212 v0.87
Modulation	QPSK,
Receiver	Linear FDE MMSE
Channel estimation	Perfect

6. References

[1] R1-102631, “Design Principles for UCI on PUSCH”, Ericsson, ST-Ericsson, RAN1#61, Montreal, Canada, 10-14 May 2010.

[2] R1-103180, “UCI Multiplexing on PUSCH in UL-MIMO Transmissions”, Motorola, RAN1#61, Montreal, Canada, 10-14 May 2010.

[3] R1-102762, “UCI multiplexing for SU-MIMO transmission”, Qualcomm Incorporated, RAN1#61, Montreal, Canada, 10-14 May 2010.

[4] R1-102827, “Data and Control Multiplexing for UL Multi-Antenna Transmission”, Texas Instruments, RAN1#61, Montreal, Canada, 10-14 May 2010.

[5] R1-102962, “Performance evaluation of UCI multiplexing schemes on PUSCH in case of SU-MIMO”, Nokia Siemens Networks, Nokia, RAN1#61, Montreal, Canada, 10-14 May 2010.

[6] 36.211, v8.8.0, “Physical Channels and Modulation”, 3GPP.