Channel selection HARQ feedback in LTE-Advanced

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Abstract—**LTE-Advanced supports carrier aggregation which implies that ACK/NACK information bits for multiple downlink carriers are fed back in the uplink. One method for HARQ feedback with multiple ACK/NACK bits is channel selection, wherein ACK/NACK information is encoded by the joint selection of a channel (transmit sequence) and a QPSK symbol. We give a signal design for mapping ACK/NACK information to the channels and modulation symbols, in order to minimize and equalize the ACK-to-NACK and NACK-to-ACK error probabilities. It is shown how the performance depends on the set of channels assigned to a given ACK/NACK bit.**

I. INTRODUCTION

LTE-Advanced was recently submitted to the ITU as a candidate radio access technology for IMT-Advanced. LTE-Advanced (i.e., LTE Rel-10) is directly building on LTE Rel-8/9 and is a backwards compatible extension with new features introduced to comply with the ITU requirements. It was found that already LTE Rel-8/9 fulfilled most of the ITU requirements [1]. However, one ITU requirement is the support of at least 40 MHz channel bandwidth and preferably up to 100 MHz. A carrier in LTE can have at most 20 MHz bandwidth and it was subsequently agreed that bandwidth extension in LTE-Advanced should be provided by means of aggregation of multiple component carriers [2]. Any carrier in LTE-Advanced could be operated as a component carrier being part of carrier aggregation or as a single standalone carrier. Thus this modular approach leverages on the already existing system design and LTE-Advanced supports aggregation of up to 5 component carriers. In practice, due to the implementation complexity, it is expected that initial deployments will accommodate at most 2 component carriers. The developed performance and RF requirements have thus far been limited to this case [3]. In the physical layer, much of the control signaling has also been optimized for the 2 component carrier case.

In LTE, the downlink (DL) data is encoded, scrambled and modulated forming a transport block (TB) comprising the modulation symbols. Upon reception of a TB, a CRC is calculated and the HARQ feedback involves sending an ACK or NACK on the uplink. For MIMO transmission on a carrier, up to 2 TBs can be transmitted simultaneously, which are further divided into at most 8 independent spatial data streams (transmission layers) in LTE-Advanced. With carrier aggregation of two component carriers in FDD, there can thus be up to 4 ACK/NACK bits to feed back. For TDD, the number of ACK/NACK bits could be even larger, since one uplink subframe carries the HARQ feedback for TBs transmitted in multiple downlink subframes.

The LTE Physical Uplink Shared Channel (PUSCH) is based on SC-FDMA (i.e., DFT-spread OFDM) to achieve low PAPR and the ACK/NACK bits can be multiplexed with the data symbols in the PUSCH. If no PUSCH is being transmitted, the ACK/NACK bits are transmitted through the Physical Uplink Control Channel (PUCCH), with transmission formats which are based on low PAPR BPSK/QPSK modulated sequences. This would allow 1/2 ACK/NACK bits to be transmitted (referred to as PUCCH Format 1a/1b). Simultaneous transmission of multiple sequences from a mobile terminal (UE) is not supported as it increases the PAPR. To accommodate the larger HARQ payload in TDD, one feedback mode in LTE Rel-8/9, is where one sequence (i.e., channel) is selected from a set of sequences and the ACK/NACK information is encoded both by the selected sequence and the QPSK symbol. This preserves low PAPR and is known as Format 1b with channel selection.

In LTE-Advanced, there are several transmission formats that could be configured to feed back HARQ information. Herein, we focus on the so called Format 1b with channel selection for the FDD case, which has been included as a means for HARQ feedback for carrier aggregation with up to 4 ACK/NACK bits for both FDD and TDD. For TDD, if the number of ACK/NACK bits exceeds 4, HARQ information compression is performed, e.g., by logical AND operation among ACK/NACK bits from different TBs (spatial bundling) or subframes (time-domain bundling). There is typically a cost of such bundling operations in terms of lower system throughput, as upon a bundled NACK, retransmissions have to be initiated also for TBs that were associated with an ACK.

In this contribution, we provide a signal design for channel selection, namely the mapping of ACK and NACK states to the signal space, i.e., the channels and the QPSK symbols. This mapping affects the probabilities of ACK-to-NACK and NACK-to-ACK errors. HARQ signaling needs to be robust, as an ACK-to-NACK error results in unnecessary retransmissions, while a NACK-to-ACK error could give packet dropping. A key observation we make is that the detection reliability is larger for the channel than for the modulation symbol. Performance for a given ACK/NACK bit will primarily depend on which set of channels that is assigned and we show how to compose the sets. Moreover, for a correctly detected channel, it is realized that ACK and NACK states should be mapped to maximally separated QPSK symbols to minimize the error probabilities. However, the joint

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allocation of channels and modulation symbols to the feedback states is nontrivial, since each combination of channel and symbol may represent a different feedback state (ACK or NACK) for different TBs. The proposed signal design criteria may, e.g., be used in exhaustive search for good mappings.

Sec. II contains a description of the signaling formats and channel selection principles. The signal design is described in Sec. III and we explain the issues addressed in the LTE standard. The receiver description is contained in Sec. IV and evaluation results are presented in Sec. V.

II. HARQ FEEDBACK IN LTE-ADVANCED

A. *LTE-Advanced Downlink Carrier Aggregation*

Carrier aggregation aims to provide very high peak data rates. However, it is expected that a UE typically will receive data on mostly one downlink carrier, which is referred to as the DL Primary Component Carrier (PCC). Upon a need for high data rate, one or several Secondary Component Carriers (SCCs) can be scheduled in parallel. The transmission on any carrier is determined by one DL assignment containing information about the format of the transmission in a subframe, which the UE is detecting in the Physical Downlink Control Channel (PDCCH). To save PDCCH overhead, it is also possible to use Semi-Persistent Scheduling (SPS) on the PCC, e.g., for small payloads as VoIP. In this case, data can be transmitted without an associated DL assignment, since resources in the data channel are reserved for several subframes ahead. Typically, the PDCCH will be transmitted on the same carrier as for which the DL assignment applies, but to handle severe interference environments, it is also possible that the PDCCH can be transmitted on a different carrier, so called cross-carrier scheduling. In any case, a TB can only be transmitted on one component carrier.

A DL assignment applies to 1 TB, or 2 TBs if MIMO is used. The feedback states associated with a TB is ACK or NACK. If the UE did not receive a DL assignment, nothing is fed back, which is referred to as Discontinuous Transmission (DTX). In the case where the base station (eNodeB) has scheduled data but the UE failed to detect the DL assignment, the eNodeB is still expecting an ACK or NACK but the UE is assuming DTX. Hence, the eNodeB has to perform DTX detection in order to re-transmit DL assignments.

B. *PUCCH Format 1b*

An uplink subframe is 1 ms long and consists of 2 slots of 0.5 ms each and a slot contains 6 or 7 OFDM symbols depending on whether extended- or normal cyclic prefix length has been configured, respectively. A resource block (RB) defines a time-frequency region of 0.5 ms and 180 kHz (i.e., 12 subcarriers). The RBs for the PUCCH are located at the edges of the carrier and a PUCCH transmission in a subframe is performed using RBs at both edges in the two different slots. OFDM symbol 0, 1, 5 and 6 carry a QPSK modulated sequence, while symbol 2, 3 and 4 carry a demodulation reference signal (DMRS) sequence. The same QPSK modulation symbol is used for OFDM symbol 0, 1, 5 and 6 and in both slots. The sequences use a QPSK alphabet and have been found through exhaustive search for obtaining low PAPR. To mitigate interference, the sequences vary between OFDM symbols as well as slots, in a predefined manner.

To increase the PUCCH multiplexing capacity, CDM of different UE's transmissions within an RB is facilitated by using different phase rotations of one basic sequence, achieved by a linear phase modulation of the basic sequence in the frequency domain [6]. Thus, 12 orthogonal sequences can be obtained within an RB from one QPSK sequence. In addition, there is also spreading in the time-domain; for OFDM symbol 0, 1, 5 and 6, length-4 orthogonal sequences are used, while for OFDM symbol 2, 3 and 4, length-3 orthogonal sequences are used. The maximum multiplexing capacity will thus be limited by the number of orthogonal DMRSs, allowing up to 3*12=36 different UEs to transmit a PUCCH in the same RB. In practice, less than 12 phase shifts will be used to preserve the orthogonality in frequency fading channels and 3*6=18 UEs/RB would be a more representative figure.

To reduce signaling overhead, the PUCCH resource/channel (i.e., QPSK sequence, spreading sequence, RB, phase rotation) to be used for a given UE is not explicitly signaled but is derived implicitly from the DL assignment. Since DL assignments for different UEs are transmitted on mutually orthogonal time-frequency resources in the PDCCH, so called Control Channel Elements (CCEs), and at least one CCE is used, an implicit mapping is defined from the CCE number representing the first CCE carrying the DL assignment to a unique PUCCH resource. For SPS, there is no associated DL assignment and the PUCCH resource is explicitly signaled by higher layers.

C. *PUCCH Format 1b with Channel Selection*

Since Format 1b only accommodates 2 ACK/NACK feedback bits, it can be combined with channel selection, where channel refers to the PUCCH resource used for transmitting information. A set of N channels (i.e., PUCCH resources) would be reserved for each UE and the combination of selected channel and associated QPSK modulation symbol provides up to $4N$ information states. These information states should encode all valid ACK, NACK and DTX combinations for M TBs, i.e., up to 3^M states. With 2 carriers aggregated, the possible values of M depend on whether the UE is configured for SIMO or MIMO transmission, i.e., M is 2 (SIMO+SIMO), 3 (SIMO+MIMO or MIMO+SIMO) or 4 (MIMO+MIMO). For this, it was decided that N=2, 3 and 4, respectively. Since $3^M > 4N$, a reduction of feedback states is needed.

The signal design problems at hand are to assign the PUCCH resources and QPSK modulation symbols to the HARQ feedback states ACK, NACK and DTX for each configured carrier, considering a number of constraints.

1) Detection Performance

The HARQ feedback detection performance should preferably be equal for all TBs as well as being low on average.

2) Resource reservation

It is crucial to allow implicit PUCCH resource reservation. This implies, e.g., that if the DL assignment on one carrier is not received (i.e., DTX), a PUCCH resource cannot be implicitly reserved from this missed DL assignment for signaling HARQ feedback concerning the other carrier, which may not be in DTX.

3) Reconfiguration of M

The value of M is semi-statically configured and reconfiguration of a carrier may take comparatively long time. Hence, there may exist periods during which the eNodeB does not know whether the UE has applied the new value of M. During such reconfiguration periods, it should still be possible to schedule the UE on the PCC without any ambiguous HARQ feedback.

4) SIMO transmissions on MIMO carrier

Even though a UE is configured for MIMO transmission, one TB could be disabled and DL assignments could schedule SIMO transmissions. In this case, the total number of scheduled TBs is smaller than the configured value M, which should also be accommodated for by the signal design.

III. ACK/NACK FEEDBACK SIGNAL DESIGN

A key observation is that the detection probability of a channel (i.e., an orthogonal sequence), which can be done by energy detection, is more reliable than the detection of a QPSK symbol, which needs phase detection. Our proposed signal design therefore builds on that certain dimensions in the signal space can be detected more reliably. We will therefore assume that errors primarily arise from detecting the modulation symbols.

A. Information mapping to constellation points

Conditioned on a correctly detected channel, an error (e.g., ACK-to-NACK or NACK-to-ACK) for TB m (m=0,1,…,M-1) occurs only if the detected constellation point encodes a feedback state for TB m, being different from the state encoded on the correct constellation point. It is thus clear that; *for a given TB m, feedback states representing the same information should be mapped to neighboring constellation points*. This should apply to all N channels and all M TBs.

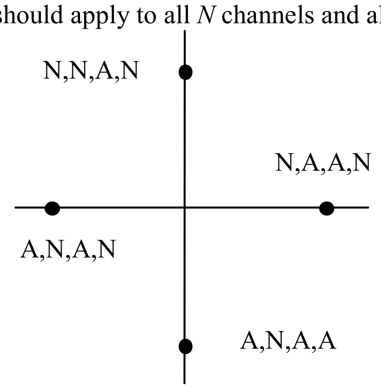

Figure 1. Constellation mapping for ACK/NACK states on one channel.

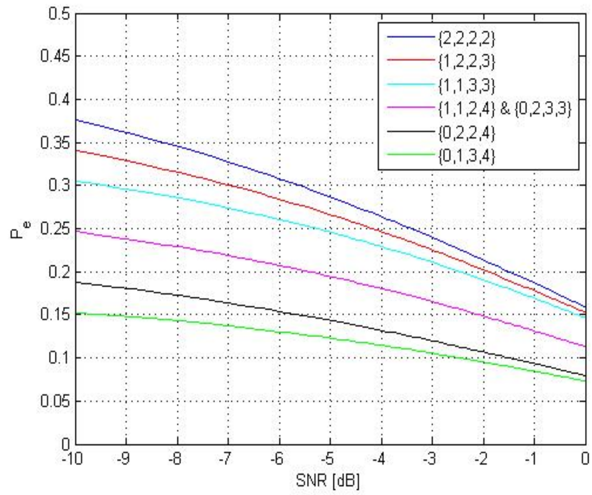

Figure 2. Error probability for different multisets $\left\{n_i^{(m)}\right\}_{i=0}^{N-1}$ for a given m.

This principle is illustrated in Fig. 1, which is depicting the mapping for channel 3 as given in Table IV, where Gray coded QPSK is assumed[1]. Furthermore, this channel encodes 2 ACKs & 2 NACKs, 1 ACK & 3 NACKs, 4 ACKs, and 1 ACK & 3 NACKs, for m=0, 1, 2 and 3, respectively. Thus for m=2, there can never be an ACK-to-NACK error, if channel 3 is correctly detected, since no constellation point encodes a NACK for m=2.

B. Information mapping to channels

Conditioned on a correctly detected channel, the error probability P_q for TB m of a feedback state, say an ACK, depends on how many constellation points on this channel that represent an ACK for the given TB. Suppose Gray coded QPSK and $p = Q\left(\sqrt{SNR}\right)$. Then, for any transmitted symbol

$$\begin{aligned}&\Pr[\text{No symbol error}] = (1-p)^2\\&\Pr[\text{Closest symbol detected}] = p(1-p)\\&\Pr[\text{Farthest symbol detected}] = p^2.\end{aligned} \tag{1}$$

If q constellation points on the given channel represent ACK, and the ACKs are mapped to the constellation points according to Sec. III.A, then an ACK-to-NACK error occurs for q=1, 2, 3 and 4, respectively, as

$$\begin{aligned}&P_1 = 1-(1-p)^2\\&P_2 = p^2 + p(1-p)\\&P_3 = 1/3\cdot p^2 + 2/3\cdot p(1-p)\\&P_4 = P_0 = 0\end{aligned} \tag{2}$$

Let $n_i^{(m)}$ denote the number of constellation points that encode an ACK on channel i (i=0,1,…,N-1) for TB m. The example of Fig. 1 would result in $n_3^{(0)} = 2$, $n_3^{(1)} = 1$, $n_3^{(2)} = 4$ and $n_3^{(3)} = 1$. Assuming that any of the constellation points are

[1] For brevity, the state N/D is replaced by N.

transmitted with a same probability, the error probability of an ACK for TB m is, conditioned on correct channel detection,

$$P_e(m) = \frac{1}{\sum_{i=0}^{N-1} n_i^{(m)}} \sum_{i=0}^{N-1} n_i^{(m)} \cdot P_{n_i^{(m)}} . \quad (3)$$

Fig. 2 contains plots of (3) for different multisets $\{n_i^{(m)}\}_{i=0}^{N-1}$ where N=4. The results show that the error probability is dependent on the formation of the multiset. We therefore conclude that, *in order to have similar performance for different TBs m, the same multiset should be used for all m.* Note that the performance is not dependent on the order of the elements in the multiset. The lowest error probability is obtained for multisets containing $n_i^{(m)} = 0$, i.e., channel i is not utilized for encoding an ACK and for $n_i^{(m)} = 4$, i.e., all constellation symbols encode an ACK on channel i. This is also realized directly from (2).

C. ACK/NACK mapping table

The nontrivial issue is to map, for each TB m, the feedback states ACK, NACK and DTX, to constellation points and channels. In other words, finding for each m, a multiset $\{n_i^{(m)}\}_{i=0}^{N-1}$. This mapping may be represented by a table but since each row represents HARQ information for all the TBs, there are interdependencies and the M multisets cannot be chosen arbitrarily. Exhaustive search has been performed and Table IV in Appendix from [4] (with A, N, D denoting ACK, NACK and DTX, respectively) contains our proposal for a mapping wherein the multiset is {1,1,2,4} for every TB m.

To reduce the number of feedback combinations, DTX has been merged with NACK wherever possible. One consequence of this is that the eNodeB cannot distinguish whether the DL assignment was missed (DTX) or if the TB was incorrectly decoded (NACK). This may give some throughput loss, since the eNodeB may not apply incremental redundancy when re-transmitting a TB which was associated with a NACK/DTX. It is assumed that TB m=0 and 1 are associated with the PCC and TB m=2 and 3 with the SCC. Since both TBs on a carrier are scheduled by one DL assignment, DTX must apply to both TBs on a carrier simultaneously. Further inspection of the table shows that the property of Sec. III.A is fulfilled. That is, for any given channel i, for any TB m, neighboring constellation points encode the same feedback state.

D. LTE-Advanced ACK/NACK mapping table

The adopted LTE-Advanced table for N=4 is Table V in Appendix [5, Table 10.1.2.2.1-5]. For the feedback state ACK, it can be found that the multisets are {2,2,4,0},{2,4,1,1},{0,4,2,2} and {0,2,3,3} for m=0,1,2 and 3, respectively. Hence, it results in 3 unique multisets, instead of 1 set as for our proposed Table IV. This suggests that the ACK/NACK detection performance will differ among the TBs. It can be verified that the constellation mapping follows the Sec. III.A principle.

If it is assumed that channel 0 and 1 are reserved from the DL assignment for the PCC, and channel 2 and 3 are reserved from the DL assignment for the SCC, both Table IV and V support implicit PUCCH resource allocation. This is realized by that channel 0 or 1 are never used when TB m=0 and 1 are in DTX; and channel 2 or 3 are never used when TB m=2 and 3 are in DTX. Furthermore, for Table V, if only the PCC is scheduled, the states of TB m=2 and 3 is DTX. In this case, it can be seen that only channel 0 will be used, i.e., there is no channel selection. This is in fact PUCCH Format 1b without channel selection, which a UE not configured with carrier aggregation (M=2) would use. Hence, there is no ambiguity for the eNodeB with regards to HARQ feedback regardless if the UE is configured with Format 1b with or without channel selection, if it schedules on the PCC only. The issue with SIMO transmission can be solved by that the UE assumes the reported feedback state for the disabled TB is the same as for the received TB. Hence, HARQ feedback for a MIMO configured carrier can be performed for SIMO without reconfiguring M.

IV. Receiver

At the receiver side, the first step is to calculate a maximum likelihood (ML) metric for each row l in the ACK/NACK table

$$\Lambda(l) = \sum_j \sum_n \left| r_{A/N}(n,j) \cdot s_{A/N}^*(l) + r_{DMRS}(n,j) \cdot s_{DMRS}^*(l) \right|^2$$

and detect the row with the maximum metric value, $l^* = \arg\max_l \Lambda(l)$, where j is receive antenna index, n is the transmission slot, $r_{A/N}(n,j)$ is the received ACK/NACK signal in slot n on receive antenna j, $r_{DMRS}(n,j)$ is the received DMRS in slot n on receive antenna j, $s_{A/N}(l)$ and $s_{DMRS}(l)$ are the signal and DMRS corresponding to the l:th row of the ACK/NACK table, respectively.

In a second step, the maximum detection metric, $\Lambda^* = \Lambda(l^*)$, is compared with a detection threshold T and if $\Lambda^* \geq T$, the receiver will assume that the ACK/NACK information of row l was transmitted; otherwise, the receiver will assume no transmission was performed, i.e., the all-DTX state.

V. Numerical Results

The following performance requirements are assumed

$$\Pr[\text{ACK-to-NACK/DTX}] \leq 10^{-2} \quad (4)$$
$$\Pr[\text{NACK-to-ACK}] \leq 10^{-3}.$$

The above error probabilities are conditioned on the NACK or ACK event. In practice, the link adaptation is typically performed such that the BLER, i.e., the probability of a

NACK, is ≈10%. The detection threshold T is set to fulfill the performance requirement of DTX detected as ACK, defined as

$$\Pr[\text{DTX-to-ACK}] = \frac{\#(\text{false ACK bits})}{\#(\text{PUCCH DTX})} \le 10^{-2}.$$

Simulations have been performed according to Table I to determine the lowest SNR for which both the requirements (4) hold, shown in Figs. 3-6 and summarized in Table II and III. An observation is that Pr[ACK-to-NACK/DTX] is always worse than Pr[NACK-to-ACK] at a certain SNR. The reason is that NACK-to-DTX is not counted as an error case for Pr[NACK-to-ACK]. Results are obtained for the proposed Table IV, comprising M=4 ACK/NACK bits and Table V. Results are also given for our proposed M=3 ACK/NACK bits table [4] and the corresponding LTE-Advanced table [5].

From Tables II and III, it can be verified that our proposals give an equal detection performance for all M TBs and slightly outperform the LTE-Advanced tables in terms of required SNR. Figs. 3 and 5 show that the LTE-Advanced mapping tables have unequal detection performance, especially for the NACK-to-ACK errors. Furthermore, the results corroborate the quantitative analysis from Sec. III. For example, for the LTE-Advanced table, the best performance is for m=0 and m=2, then for m=1 and m=3. Also, the performance is equalized for m=0 and m=2, and for m=1 and m=3. These properties could be deduced from the corresponding multisets in Sec. III. D and the order of the curves in Fig. 2. Hence, our analysis provides performance prediction for ACK/NACK tables and indication of desirable multisets to be obtained from exhaustive search.

TABLE I. SIMULATION ASSUMPTIONS

Parameter	Value
Carrier frequency	2 GHz
Channel model	ETU/5MHz
Velocity	3 km/h
Antenna configuration	1 TX×2 RX
RX antenna correlation	Uncorrelated
Cyclic prefix	Normal
Signal bandwidth	180 kHz
Multiplexing capacity	18 UEs/RB

TABLE II. PERFORMANCE COMPARISON FOR 3 BITS ACK/NACK

	SNR @ 10^{-3} NACK-to-ACK			**SNR @ 10^{-2} ACK-to-NACK/DTX**			**Required SNR (dB)**
	m=0	***m=1***	***m=2***	***m=0***	***m=1***	***m=2***	
Proposed	-6.8	-6.8	-6.8	-6.6	-6.6	-6.6	-6.6
Rel-10	-6.5	-6.5	-12.4	-6.7	-6.5	-6.5	-6.5

TABLE III. PERFORMANCE COMPARISON FOR 4 BITS ACK/NACK

	SNR @ 10^{-3} NACK-to-ACK				**SNR @ 10^{-2} ACK-to-NACK/DTX**				**Required SNR (dB)**
	m=0	***m=1***	***m=2***	***m=3***	***m=0***	***m=1***	***m=2***	***m=3***	
Proposed	-6.4	-6.4	-6.4	-6.4	-6.2	-6.2	-6.2	-6.2	-6.2
Rel-10	-7.0	-6.4	-7.0	-6.4	-6.2	-6.2	-6.2	-6.2	-6.2

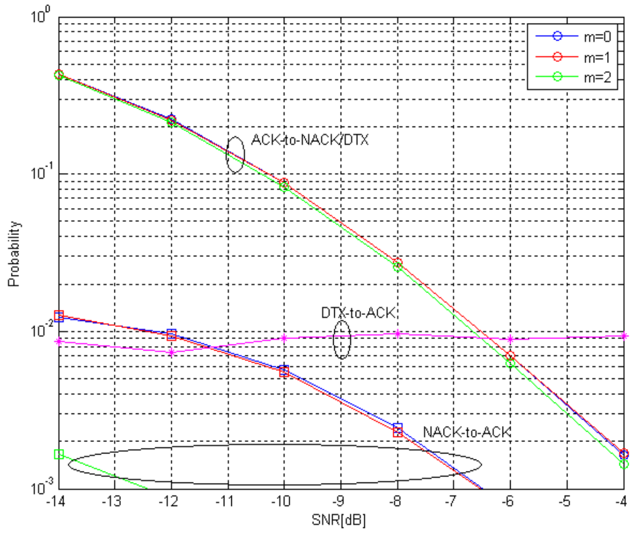

Figure 3. LTE-Advanced 3 bits ACK/NACK mapping table.

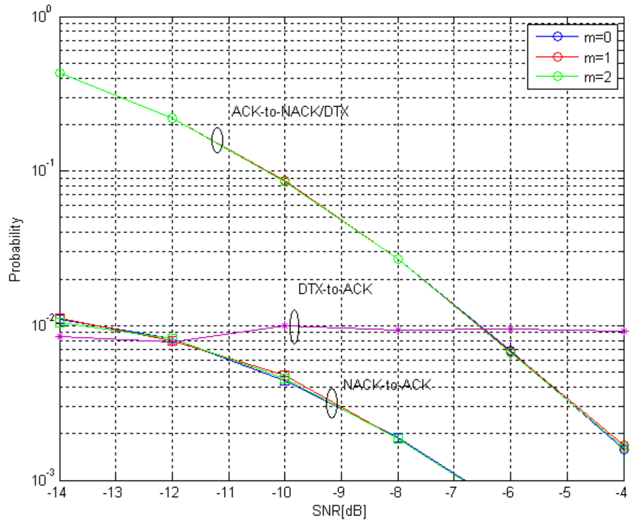

Figure 4. Proposed 3 bits ACK/NACK mapping table.

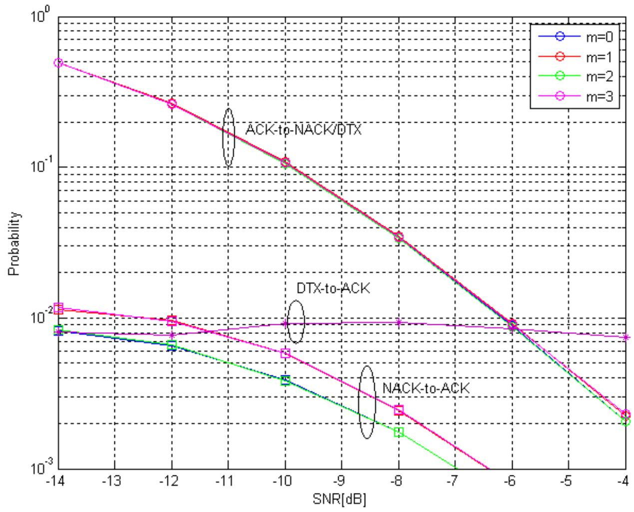

Figure 5. LTE-Advanced 4 bits ACK/NACK mapping table.

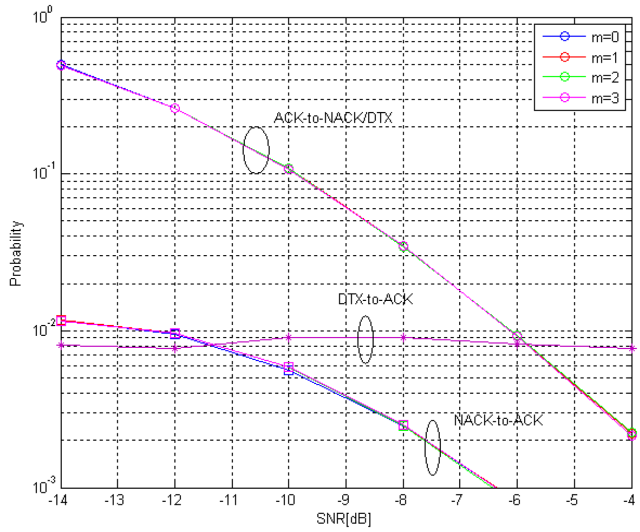

Figure 6. Proposed 4 bits ACK/NACK mapping table.

VI. CONCLUSIONS

We showed that proper signal design for channel selection is largely determined by finding suitable multisets comprising the channels encoding a certain feedback state. However, constructing ACK/NACK mapping tables is nontrivial and suitable multisets were obtained though exhaustive search. Once, such multisets have been found, feedback states representing the same information should be mapped to neighboring constellation points.

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APPENDIX

TABLE IV. ACK/NACK MAPPING TABLE FOR *N*=4 [4]

Feedback States				**Signal**	
Transport block m				***Channel***	***QPSK***
0	***1***	***2***	***3***		
A	A	A	A	1	'11'
A	A	A	N/D	1	'01'
A	A	N/D	A	1	'10'
A	A	N/D	N/D	1	'00'
A	N/D	A	A	3	'01'
A	N/D	A	N/D	3	'11'
A	N/D	N/D	A	2	'11'
A	N /D	N/D	N/D	0	'10'
N/D	A	A	A	0	'11'
N/D	A	A	N/D	3	'00'
N/D	A	N/D	A	2	'00'
N/D	A	N/D	N/D	0	'01'
N/D	N/D	A	A	2	'10'
N/D	N/D	A	N/D	3	'10'
N/D	N/D	N/D	A	2	'01'
N	N	N/D	N/D	0	'00'
D	D	D	D	No transmission	

TABLE V. ACK/NACK MAPPING TABLE FOR *N*=4 [5]

Feedback States				**Signal**	
Transport block m				***Channel***	***QPSK***
0	***1***	***2***	***3***		
A	A	A	A	1	'11'
A	A	A	N/D	1	'10'
A	A	N/D	A	2	'11'
A	A	N/D	N/D	0	'11'
A	N/D	A	A	2	'01'
A	N/D	A	N/D	2	'00'
A	N/D	N/D	A	2	'10'
A	N /D	N/D	N/D	0	'10'
N/D	A	A	A	1	'01'
N/D	A	A	N/D	1	'00'
N/D	A	N/D	A	3	'01'
N/D	A	N/D	N/D	0	'01'
N/D	N/D	A	A	3	'11'
N/D	N/D	A	N/D	3	'10'
N/D	N/D	N/D	A	3	'00'
N/D	N	N/D	N/D	0	'00'
N	N/D	N/D	N/D	0	'00'
D	D	D	D	No transmission	