A Turbo-Like Iterative Decoding Algorithm for Network Coded HARQ

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***Abstract*—This paper proposes a turbo-like decoding algorithm for network coded HARQ (NC-HARQ) retransmission scheme. Instead of retransmission erroneous packets individually, we send a network coded packet formed by XOR of two incorrectly received packets in the NC-HARQ retransmission. With respect to the two initial packets and one network coded packet, this retransmission scheme can be viewed as a product code based on the Turbo coding principle. We develop an iterative decoding algorithm for the proposed NC-HARQ scheme. The algorithm uses the log-likelihood ratios generated by decoding any two packets to calculate a priori information for the third one. This approach is applicable for both Chase Combing (CC) and Incremental Redundancy (IR). Furthermore, a link adaptation algorithm is investigated for the proposed network coded HARQ scheme. LTE link-level simulations confirm the throughput enhancement by the proposed scheme compared to common HARQ transmission.**

***Index Terms*—Network coding, HARQ, iterative decoding, link adaptation.**

I. INTRODUCTION

Recently, network coding (NC) has been proposed to increase the system throughput for error-free networks [1]. In [2], it has been shown useful for wireless communications. Many modern communication systems apply hybrid automatic repeat request (HARQ) techniques to improve the system throughput. There are two favorable types of HARQ approaches, i.e., Chase Combining (CC) and Incremental Redundancy (IR) [3]. Chase Combining explores retransmission of identical packets while Incremental Redundancy combines packets determined by varying puncturing patterns, i.e., different redundancy versions [4], [5]. Combining network coding and HARQ techniques for multicast and multiuser scenarios has been studied in [6], [7]. They apply network coding principle across the packets of different users. Besides, [8], [9] research network coding technique for multicast and broadcast schemes.

The idea of link adaptation is to adjust the modulation and coding scheme (MCS) efficiently in actual channel conditions [10], [11]. By selecting of optimal combination of modulation and coding scheme, the system utilizes the physical resources effectively and makes the most out of a time varying channel.

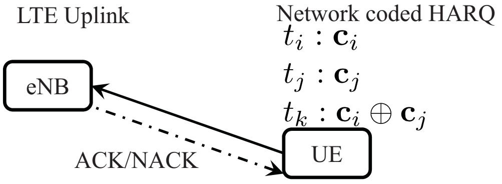

Fig. 1. Network coded HARQ in LTE uplink unicast scenario, where in the third time slot a network coded packet $\mathbf{c}_i \oplus \mathbf{c}_j$ is transmitted to eNB.

In [12], the authors have presented the application of network coded HARQ (NC-HARQ) for point-to-point transmission without intermediate nodes, as shown in Fig. 1. Instead of retransmission erroneous packets $\mathbf{c}_i$ and $\mathbf{c}_j$ individually, we send a network coded packet formed by XOR of two incorrectly received packets $\mathbf{c}_k$ in the NC-HARQ retransmission. A simple detection algorithm for NC-HARQ scheme has been proposed.

In this paper, the main contributions is developing a turbo-like iterative decoding algorithm for NC-HARQ based on Turbo coding principle. This approach is applicable for both CC and IR. Further, we develop a link adaptation algorithm that satisfies a given target block error rate (BLER) while maximizing the throughput.

The remainder of this paper is organized as follows. Section II introduces the system model to the network coded HARQ for unicast uplink transmission. In Section III we present an iterative decoding algorithm for CC and IR. In Section IV, a link adaptation algorithm is investigated. The performance is assessed by simulation results in Section V. Section VI will conclude this paper.

II. SYSTEM MODEL OF NC-HARQ

A. Mathematical Description

In this paper, we consider the application of NC-HARQ for LTE uplink transmissions. The user equipment (UE) wishes to send packets to an evolved Node B (eNB) controlled by individual HARQ processes. At UE, the information vector $\mathbf{a}_i \in \mathbb{F}_2^{N_a}$ in time slot t_i is encoded by the standard LTE turbo encoder yielding the codeword $\mathbf{b}_i \in \mathbb{F}_2^{N_b}$ [13],

$$\mathbf{b}_i = \Gamma(\mathbf{a}_i). \tag{1}$$

This systematic encoder consists of parallel concatenation of two recursive convolutional codes with code rate $R = \frac{N_a}{N_b} = 1/3$. By applying LTE rate-matching, we achieve the rate-matched output $\mathbf{c}_i^r \in \mathbb{F}_2^{N_c}$, where r indexes the redundancy version

$$\mathbf{c}_i^r = \mathrm{RM}(\mathbf{b}_i). \tag{2}$$

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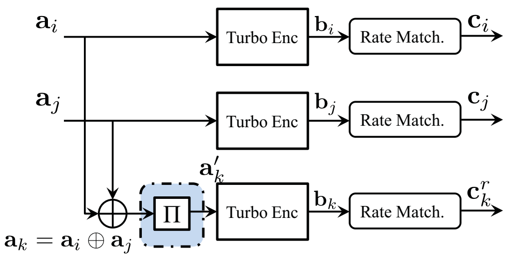


Fig. 2. Network coded retransmission can be viewed as a two dimension code with LTE turbo code as horizontal code and single parity check code as vertical code.

The current transport format and redundancy version determine LTE rate-matching. Therefore, $R_c = \frac{N_a}{N_c}$ gives the effective code rate of the initial transmission. Furthermore, after every retransmission, the code corresponds to a lower rate code. The code bits are modulated to symbols $\mathbf{x}_i \in \mathbb{X}^{N_x}$ (e.g., QPSK, 16-QAM or 64-QAM) and transmitted to the eNB.

In case of block fading channel, the received signal vector in time slot t_i is given by

$$\mathbf{y}_i = h_i \mathbf{x}_i + \mathbf{n}_i \ , \tag{3}$$

where $\mathbf{n}_i$ is the noise vector whose elements are independently identically distributed (i.i.d) zero-mean Gaussian random variables with variance σ^2. The coefficient h_i denotes complex zero-mean circular symmetric Gaussian distributed variable with variance one.

Based on the received signal $y_{i,n}$, we can calculate the Log-Likelihood-Ratios (LLRs) for the participating coded bit $c_{i,m}$ by

$$\mathrm{L}_{\mathrm{Dem}}(c_{i,m}) = \ln \frac{\sum_{x \in \mathbb{X}, c_{i,m}=0} \exp\left(-\frac{|y_{i,n} - h_i x|^2}{\sigma^2}\right)}{\sum_{x \in \mathbb{X}, c_{i,m}=1} \exp\left(-\frac{|y_{i,n} - h_i x|^2}{\sigma^2}\right)} \ .$$

To calculate the probability of $c_{i,m} = 0$ (or $c_{i,m} = 1$), all possible symbols $x \in \mathbb{X}$ related to $c_{i,m} = 0$ (or $c_{i,m} = 1$) need to be considered.

B. NC-HARQ with Chase Combining (NC-HARQ-CC) and Incremental Redundancy (NC-HARQ-IR)

Fig. 2 illustrates the transmission procedure of NC-HARQ for LTE uplink unicast transmissions. The basic idea of CC is that retransmission packets have the same redundancy version as the initial packet [4]. In contrast, IR scheme transmits the message with different redundancy version at such retransmission so that more parity check bits are available for a reliable decoding [5]. Therefore, CC can be considered as a special case of IR with the same redundancy pattern.

We denote $\mathbf{c}_i$ and $\mathbf{c}_j$ as two incorrectly received packets. The transmission procedure of NC-HARQ is listed as follows

1) $\mathbf{c}_i$ is transmitted in time slot t_i controlled by HARQ process $\#i$ and $\mathbf{y}_i$ is received and decoded. Due to decoding failure the eNB sends NACK_i to the UE.
2) $\mathbf{c}_j$ is transmitted in time slot t_j controlled by HARQ process $\#j$ and $\mathbf{y}_j$ is received and decoded. Due to decoding failure the eNB sends NACK_j to the UE.
3) A network coded information word based on the XOR combination of the two information words for retransmission is constructed by

$$\mathbf{a}_k = \mathbf{a}_i \oplus \mathbf{a}_j \ . \tag{4}$$

A pseudo-random interleaver denoted by Π is applied to increase the Hamming weights for the further turbo encoding, i.e.,

$$\mathbf{a}'_k = \Pi(\mathbf{a}_k) \ . \tag{5}$$

Then, $\mathbf{a}'_k$ will be encoded by the LTE turbo code to $\mathbf{b}_k$ and rate-matched to $\mathbf{c}_k^r$. Here,

- in case of CC: the same redundancy version as the initial packets is applied (for simplicity, we ignore the superscript r.)
- in case of IR: a different redundancy version r is used according to LTE standards.

$\mathbf{c}_k^r$ is transmitted and $\mathbf{y}_k$ is received at the eNB.

4) From the received signal $\mathbf{y}_i$, $\mathbf{y}_j$ in the initial transmissions and $\mathbf{y}_k$ in the retransmission, the eNB aims to reconstruct the codewords $\mathbf{b}_i$ and $\mathbf{b}_j$ by means of adequate detection algorithms.
5) Based on the decoding success ACK/NACK messages are transmitted for both packets to the UE.
6) If any packet is still incorrectly decoded, we need to consider different retransmission cases, which is to be considered in the next section.

Note that we combine any two erroneous packets belonging to different HARQ processes in a flexible way. To do the network-coded retransmission with consideration of transmission delay constraint, we introduce a time window so that any two erroneous packets within such time windows can be combined for retransmission. In the following investigation, a time window with 8 time slots is assumed.

C. Different Retransmission Cases

For further retransmission, we can distinguish the decoding result after one network coded retransmission in three cases as follows

- Case I: if both packets can be correctly decoded, eNB sends ACK_i and ACK_j back to UE to complete the communication for message i and j.
- Case II: if only one packet can be correctly decoded, UE will switch to common HARQ to retransmit the erroneous packet.
- Case III: if both packets can not be correctly decoded, UE will retransmit the message according to a cyclic pattern $(\mathbf{c}_i, \mathbf{c}_j, \mathbf{c}_k)$, i.e., at the next time slot UE transmits $\mathbf{c}_i$ again and so on.

Note that the network coding leads to correlation of two packets so that any packet can affect the other when applying joint decoding. Therefore, it is reasonable to choose such a pattern to avoid bad quality of any one packet.

D. Different Interleaving Options

Instead of the scheme discussed above (Option I), there are several interleaving options that are also applied, which summarized as follows

- *Option II:* pseudo-random interleaver on the rate-matched codeword $\mathbf{c}_k$,

$$\mathbf{c}'_k = \Pi(\mathbf{c}_k) = \Pi(\mathbf{c}_i \oplus \mathbf{c}_j), \tag{6}$$

- *Option III:* pseudo-random interleaver on one of the information word $\mathbf{a}_i$ or $\mathbf{a}_j$,

$$\mathbf{a}_k = \mathbf{a}'_i \oplus \mathbf{a}_j = \Pi(\mathbf{a}_i) \oplus \mathbf{a}_j. \tag{7}$$

Depending on the position where the interleaver is applied, the iterative decoding structures are only with minimum differences, i.e., we apply interleaving and deinterleaving at different place when performing iterative decoding.

III. ITERATIVE DECODING ALGORITHM

In this section, we will develop an iterative decoding algorithm to perform joint decoding based on the two initial transmissions and one network coded retransmission. It is applicable for both NC-HARQ-CC and NC-HARQ-IR.

A. Decoding Procedure

As mentioned, the network-coded HARQ retransmission scheme can be viewed as a product code (serial concatenated code) as shown in Fig. 2. The product encoder is a cascaded code with the $1/3$ rate LTE turbo code as horizontal code and a $2/3$ rate single parity check code as vertical code.

The decoder structure is illustrated in Fig. 3. Based on the received signal, we can calculate the LLRs denoted as $\mathrm{L}_{\mathrm{Dem}}(\mathbf{c}_i)$, $\mathrm{L}_{\mathrm{Dem}}(\mathbf{c}_j)$ and $\mathrm{L}_{\mathrm{Dem}}(\mathbf{c}^r_k)$. Note that the turbo decoder is based on the codewords $\mathbf{b}_i$, $\mathbf{b}_i$ and $\mathbf{b}_k$. Hence, we need to rate de-match the LLRs from the demappers for turbo decoding [13]. The rate dematching in LTE system performs interleaving, puncturing and summation of LLRs with respect to the current transport format [13], i.e.,

$$\begin{aligned} \mathrm{L}_{\mathrm{Dem}}(\mathbf{c}_i) &\rightarrow \mathrm{L}_{\mathrm{Dem}}(\mathbf{b}_i), \\ \mathrm{L}_{\mathrm{Dem}}(\mathbf{c}_j) &\rightarrow \mathrm{L}_{\mathrm{Dem}}(\mathbf{b}_j), \\ \mathrm{L}_{\mathrm{Dem}}(\mathbf{c}^r_k) &\rightarrow \mathrm{L}_{\mathrm{Dem}}(\mathbf{b}_k). \end{aligned} \tag{8}$$

We use N_{H} and N_{V} to denote the iteration number of horizontal (turbo code) and vertical (single parity check code) code, respectively. The decoding process can be described briefly as follows,

1) *Decoding $\mathbf{b}_i$:* after N_{H} turbo decoding iterations, the extrinsic information for $\mathbf{a}_i$ is obtained at the output of the turbo decoder, denoted by $\mathrm{L}_{\mathrm{Ext}}(\mathbf{a}_i)$.
2) *Decoding $\mathbf{b}_j$:* similarly, the extrinsic information $\mathrm{L}_{\mathrm{Ext}}(\mathbf{a}_j)$ for $\mathbf{a}_j$ is achieved after N_{H} iterations.
3) *Decoding $\mathbf{b}_k$:* due to the linearity of LTE turbo coding and rate matching, the XOR of information words is coincident with XOR of turbo codewords, i.e.,

$$\mathbf{a}'_k = \Pi(\mathbf{a}_i \oplus \mathbf{a}_j) \leftrightarrow \mathbf{b}_k = \Pi(\mathbf{b}_i \oplus \mathbf{b}_j). \tag{9}$$

Hence, we can calculate the a-priori information of any one information word by the extrinsic information of the other two information words by means of the boxplus operation $\boxplus$ [14]. Since the initial packets are already decoded and the extrinsic information is available, the *interleaved* a-priori information for $\mathbf{a}'_k$ can be calculated

$$\mathrm{L}_{\mathrm{a}}(\mathbf{a}'_k) = \Pi(\mathrm{L}_{\mathrm{Ext}}(\mathbf{a}_i) \boxplus \mathrm{L}_{\mathrm{Ext}}(\mathbf{a}_j)). \tag{10}$$

After N_{H} iterations, the extrinsic information $\mathrm{L}_{\mathrm{Ext}}(\mathbf{a}_k)$ is achieved.

4) *Extrinsic information exchange:* similarly, the extrinsic information $\mathrm{L}_{\mathrm{Ext}}(\mathbf{a}'_k)$ can be used to calculate a-priori information for the two other decoders by boxplus operation yielding $\mathrm{L}_{\mathrm{a}}(\mathbf{a}_i)$ and $\mathrm{L}_{\mathrm{a}}(\mathbf{a}_j)$. Note that $\mathrm{L}_{\mathrm{Ext}}(\mathbf{a}'_k)$ needs to be deinterleaved,

$$\mathrm{L}_{\mathrm{a}}(\mathbf{a}_i) = \mathrm{L}_{\mathrm{Ext}}(\mathbf{a}_j) \boxplus \Pi^{-1}(\mathrm{L}_{\mathrm{Ext}}(\mathbf{a}'_k)), \tag{11a}$$

$$\mathrm{L}_{\mathrm{a}}(\mathbf{a}_j) = \mathrm{L}_{\mathrm{Ext}}(\mathbf{a}_i) \boxplus \Pi^{-1}(\mathrm{L}_{\mathrm{Ext}}(\mathbf{a}'_k)). \tag{11b}$$

5) *Iterative decoding procedure:* the decoding procedure can be repeated in N_{V} iterations among the above steps. Finally, we can obtain the final LLRs of both packets $\mathrm{L}_{\mathrm{Dec}}(\mathbf{a}_i)$ and $\mathrm{L}_{\mathrm{Dec}}(\mathbf{a}_j)$ to estimate $\mathbf{a}_i$ and $\mathbf{a}_j$.

B. Complexity Analysis

In the sequel, we discuss the complexity of the proposed NC-HARQ decoding strategy shortly. Obviously, the total number of iterations can indicate approximately the complexity of the algorithms.

We use N^0_{H} to denote the iteration number of turbo decoder when decoding the initial packets. N_{H} and N_{V} indicate the iteration number of the horizontal and vertical code, respectively. We assume that eNB can receive two packets correctly by one retransmission of each packet for common HARQ and one joint network coded retransmission for NC-HARQ. The total number of iterations for common HARQ is $2 \times N^0_{\mathrm{H}} + 2 \times N^0_{\mathrm{H}} = 4 \times N^0_{\mathrm{H}}$, i.e. it requires 32 iterations for $N^0_{\mathrm{H}} = 8$. The number of iterations for NC-HARQ is $2 \times N^0_{\mathrm{H}} + 3 \times N_{\mathrm{H}} \times N_{\mathrm{V}} = 40$ for $N^0_{\mathrm{H}} = 8$, $N_{\mathrm{H}} = 1$ and $N_{\mathrm{V}} = 8$. Using NC-HARQ increases the complexity slightly compared with common HARQ.

IV. LINK ADAPTATION

In the above sections we have considered the signal processing procedure of NC-HARQ and its performance assessments. In the sequel, we will develop a link adaptation algorithm for NC-HARQ scheme.

Generally, the task of link adaptation is to adapt the modulation coding scheme (MCS) so that a certain given objective can be achieved. Herein, we develop a link adaptation algorithm for NC-HARQ to satisfy a given target BLER and meanwhile maximize the throughput of NC-HARQ. Note that in the following investigation, constant transmission power is assumed, i.e., there is no power adaptation. Moreover, if the link adaptation chooses one MCS for initial transmission, the MCS is also unchanged during network coded retransmission.

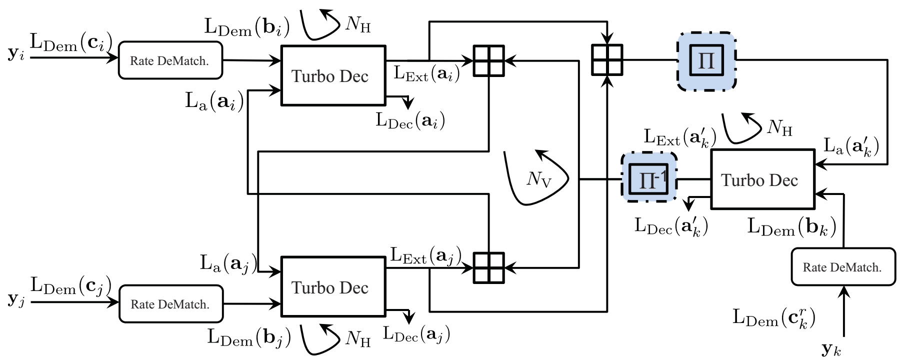


Fig. 3. Generalized iterative decoding structure for CC and IR with where ⊞ denotes boxplus operation.

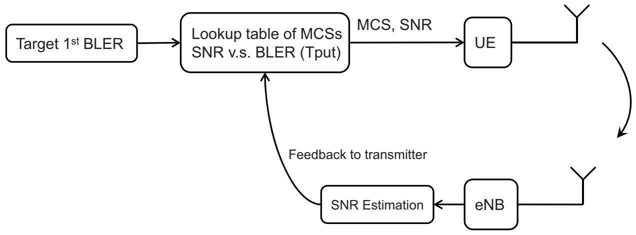


Fig. 4. Link adaptation to ensure a given the first target BLER while maximizing the throughput. Herein, perfect SNR information and a lookup table indicating the relationship of SNR and BLER are available to UE.

The same assumption is also made for common HARQ for fair comparison.

A lookup table that indicates the relationship between SNR and throughput of the first transmission for each MCS needs to be pre-simulated. It will be utilized for suitable MCS selection in link adaptation algorithm.

The procedure of the proposed link adaptation algorithm is shown in Fig. 4. Based on the estimated SNR from eNB and a required target BLER of initial transmission, UE will search in the lookup table to find out with which SNR and which MCS, that can achieve the target BLER and also maximum throughput. Then UE starts to transmit the initial packet with the determined SNR and MCS. These configuration remains unchanged until the packets are correctly received or the maximum number of retransmission is reached. After that, eNB feedbacks the current SNR estimation to UE. Based this SNR, the link adaptation algorithm will run again to choose a suitable MCS. Note that for different channel profiles, the corresponding lookup tables (throughput v.s. SNR curves) for link adaptation need to be simulated.

V. PERFORMANCE EVALUATION

A. Iterative Decoding Algorithm

In this section, we present the simulation results in a LTE link-level simulator regarding to the proposed iterative decoding algorithms. The detailed parameters setup of the LTE uplink simulator is summarized in TableI and Table II shows the transport formats used in this paper.

Parameters	Setup
Bandwidth	20 MHz
Carrier frequency	2.3 GHz
Modulation	QPSK, 16-QAM
Turbo code rate	1/3
Number of antennas (UE)	1
Number of antennas (eNB)	2
Max. number of retransmission	4

TABLE I
System parameters for LTE uplink simulations.

Transport format	N_a	N_c	Q_m	Coderate R_c
I	408	528	16QAM	0.8182
II	1608	2640	16QAM	0.6182

TABLE II
Different Transport Formats.

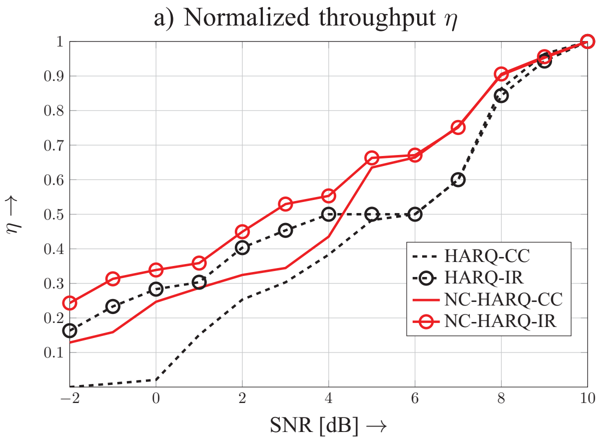
The normalized throughput is considered as key performance measurement given by

$$\eta = \frac{N_{\text{correct}}}{N_{\text{total}}}\,, \tag{12}$$

where N_{correct} denotes the number of packets that are correctly decoded and N_{total} indicates the total number of transmitted packets. To indicate the performance enhancement, the relative throughput gain of NC-HARQ in comparison with common HARQ is given by

$$\gamma = \frac{\eta_{\text{NC-HARQ}} - \eta_{\text{HARQ}}}{\eta_{\text{HARQ}}}\,. \tag{13}$$

Fig. 5 shows the throughput comparison of NC-HARQ and HARQ for AWGN channels with transport format I. NC-HARQ outperforms common HARQ with respect to the effective throughput. It can be observed for SNR= 3dB that NC-HARQ reaches the $\eta = 2/3$ normalized throughput while common HARQ achieves $\eta = 1/2$ normalized throughput. For this SNR, NC-HARQ can recover both packets by only one network coded retransmission while common HARQ requires two retransmissions. For the relative throughput gain shown in b), NC-HARQ-CC achieve better performance than that of NC-HARQ-IR. This is because we transmit different


a) Normalized throughput η

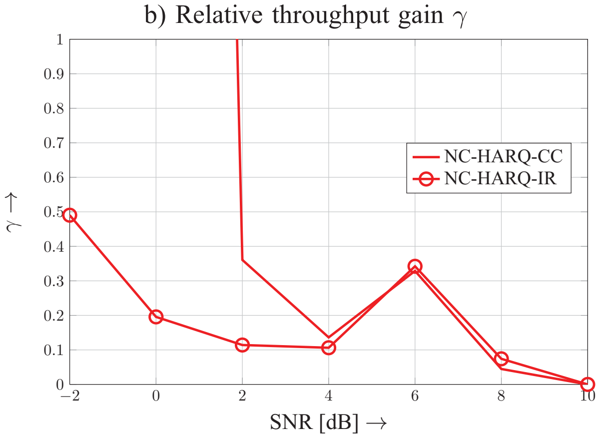

b) Relative throughput gain γ

Fig. 5. Throughput performance of common HARQ and network coded HARQ for AWGN channel with transport format I. a): throughput; b): relative gain.

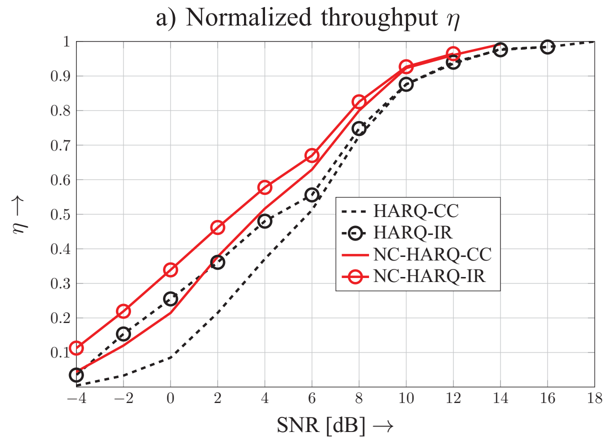
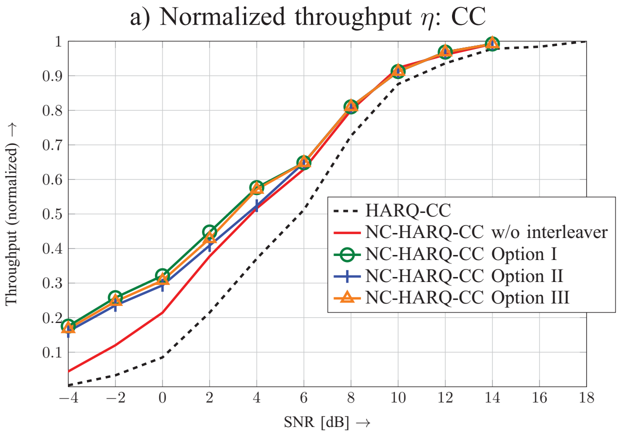

a) Normalized throughput η

Fig. 6. Throughput performance of common HARQ and network coded HARQ for EPA channel with UE speed 3km/h with transport format number II.


a) Normalized throughput η: CC

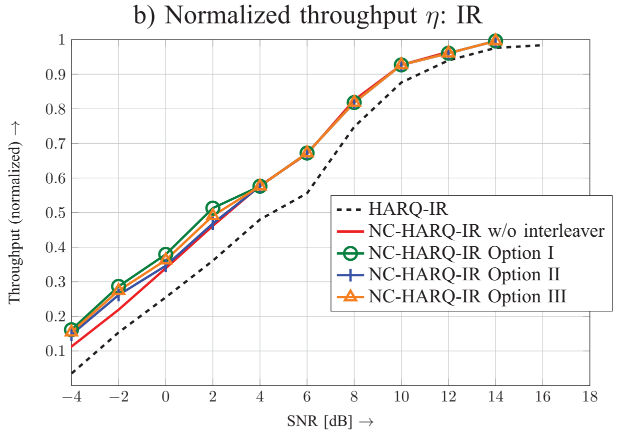

b) Normalized throughput η: IR

Fig. 7. Throughput performance of different interleaving options for EPA channel with transport format number 20. a): CC; b): IR.

redundancy versions with IR that it can construct a relative strong code than CC. The benefit introduced by NC-HARQ is relatively less significant for IR.

Fig. 6 depicts the throughput for a extended pedestrian A model (EPA) channel with UE speed 3 km/h with transport format number II [15]. For low-to-moderate SNR, NC-HARQ can achieve more than 20% throughput gain over common HARQ. Especially for NC-HARQ-CC, the gain is significant. Similar to Fig. 5, the enhancement of NC-HARQ-IR is less than that of NC-HARQ-CC.

Fig. 7 depicts the throughput of the different interleaving options of NC-HARQ-CC and NC-HARQ-IR for extended pedestrian a model (EPA) channel. We can obtain the best performance by Option I. By introducing interleaver at NC-HARQ retransmissions, the distance of each codeword can be increased so that the joint decoding property can be improved.

Fig. 8 shows the impact of the number of horizontal and vertical iterations for NC-HARQ-CC. It has been shown that the configuration set ($N_{\mathrm{H}} = 1$, $N_{\mathrm{V}} = 8$) achieves the best performance, especially for low SNR. More frequently exchanging information between horizontal and vertical codes, more reliable information can be provided by the decoder. Note that the configuration of $N_{\mathrm{H}} = 8$ and $N_{\mathrm{V}} = 1$ is exactly corresponding to the simple decoder introduced in [12]. The iterative information exchange between turbo decoders leads to faster convergence time and better decoding performance.

B. Link Adaptation

We consider the performance of link adaptation for EPA channel with UE speed of 3 km/h. The available MCSs used

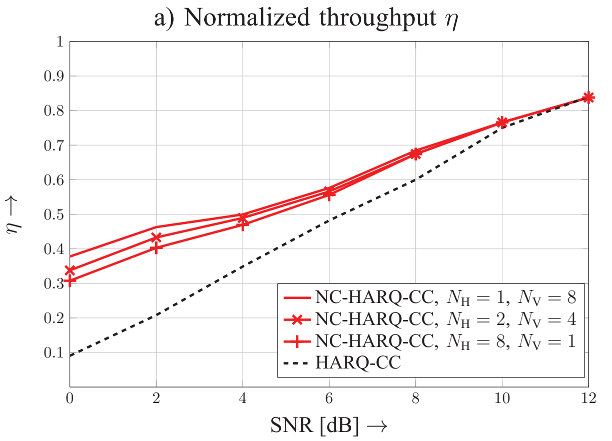


Fig. 8. Throughput performance of NC-HARQ-CC over 1-path Rayleigh fading channel with UE speed 50km/h with transport format I.

in the LTE uplink simulator is listed in Table III

Transport format (MCS)	N_a	N_c	Q_m	Coderate R_c
0	16	264	QPSK	0.1515
1	24	264	QPSK	0.1818
2	32	264	QPSK	0.2121
3	40	264	QPSK	0.2424
4	56	264	QPSK	0.3030
5	72	264	QPSK	0.3636
6	104	264	QPSK	0.4848
7	120	264	QPSK	0.5455
8	136	264	QPSK	0.6061
9	144	264	QPSK	0.6364
10	144	528	16QAM	0.3182
11	176	528	16QAM	0.3788
12	208	528	16QAM	0.4394
13	224	528	16QAM	0.4697
14	258	528	16QAM	0.5303
15	280	528	16QAM	0.5758
16	328	528	16QAM	0.6667
17	336	528	16QAM	0.6818
18	376	528	16QAM	0.7576
19	408	528	16QAM	0.8182

TABLE III
Available MCSs

For a given target BLER 90% of the initial transmission, Fig. 9 shows the throughput comparison of three different schemes, namely common HARQ without link adaptation, common HARQ with link adaptation and NC-HARQ with link adaptation. For EPA channel, link adaptation achieves significant gain because the actual channel condition can be fully exploited and the suitable MCS is selected in an optimal way. Additionally, NC-HARQ can further improve the throughput gain. The throughput gain can be observed in almost all SNR region.

VI. CONCLUSION

In this paper, we have introduced a NC-HARQ retransmission scheme for LTE uplink. In NC-HARQ, we combine two erroneous packets from different HARQ processes by means of XOR. A turbo-like iterative decoding algorithm for NC-HARQ is proposed for joint decoding of the initial packets and network-coded packet. Simulation results in the LTE uplink simulator confirm the performance enhancement by NC-HARQ. Moreover, a link adaptation algorithm for NC-HARQ is developed to further improve the throughput performance of NC-HARQ.

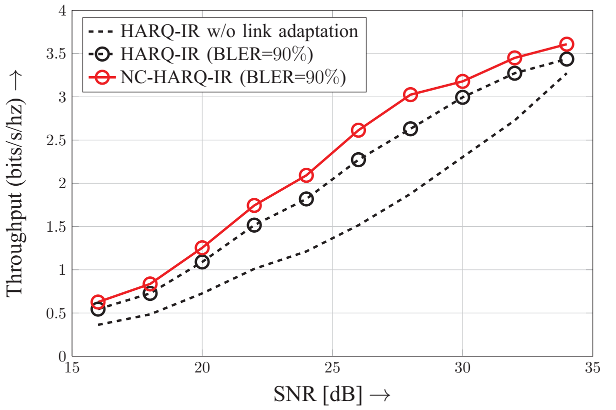


Fig. 9. Throughput v.s. SNR over EPA channel for 1_{st} target BLER 90%

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