Link Level Performance Assessment of Reliability-Based HARQ Schemes in LTE

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***Abstract*—This paper discusses two approaches of reliability-based HARQ, adapting the packet size of a retransmission in a 3GPP Long Term Evolution (LTE) system. We focus on the adaptation of the retransmission size in terms of physical resources by using information 1) of the channel, namely the signal-to-noise ratio (SNR) or 2) reliability information from the decoder output, taking the overall transmission into account. Both approaches will be compared to the HARQ system used in LTE in terms of throughput performance. Link level simulations will be performed with single bit feedback and 2 bit multilevel ACK/NAK. This work takes realistic impairments such as channel estimation, signal-to-noise ratio (SNR) estimation and implementation of a Turbo en- and decoder into regard.**

***Index Terms*—HARQ, LTE uplink, Link Adaptation, Multilevel Acknowledgement, Reliability-based HARQ.**

I. Introduction

At nowadays communication systems Hybrid-ARQ (HARQ) schemes with only a single bit Acknowledgement (ACK) are widely used to guarantee reliable communication. Reliability-based HARQ schemes using reliability information of the actual transmission quality are analyzed analytically in [1], [2] and [3]. Therein reliability information i.e. log-likelihood ratios (LLRs) stemming from the output of the channel decoder (e.g. reliability output viterbi algorithm (ROVA) or the BCJR decoder, [4], [5], respectively) is used to identify code bits, which should be retransmitted in the next instance. Those unreliable code bits identified by a small absolute value of the LLRs will be retransmitted at the cost transmitting the indices's of the corresponding codebits. By reducing this overhead, the authors of [6] and [7] have proposed to predict the retransmission size by the average of the absolute value of all LLRs. Instead of using the LLRs, [8] proposes to use the bit error probability (BEP) to decide for a retransmission in terms of transmitting an ACK/NAK. All these approaches take the decoding procedure by using the LLRs into account. Another approach is based on the mutual information between the transmitter and the receiver, like in [9] and [10]. There, the outage probability is calculated to predict the next retransmission size using some kind of accumulated mutual information (ACMI). [11] and [12] focus on maximizing the throughput by a given number of possible retransmissions with flexible and fixed retransmission size, respectively.

Motivated by [8], we propose to use the BEP to predict the retransmission size of a HARQ transmission in terms of physical resource blocks in LTE. Additionally, we reduce the overhead for the feedback to a 2 bit multilevel ACK/NAK, similar to [13], and we look at an erroneous feedback link. We will compare our approach to the outage probability based prediction of [10] in terms of throughput performance measurements and delay performance in link level simulation including realistic impairments, like estimation errors and approximations of Turbo decoding into account.

The remainder of this paper is organized as follows. Section II introduces the general system model of a transmission chain. In Section III both proposed retransmission schemes are introduced. The throughput performance is investigated by means of simulation results in Section IV. Conclusions follow in Section V.

II. System model

First, we give a brief overview of the LTE uplink transmission scheme and the principle of LTE uplink HARQ, however reliability based HARQ can be similarly applied in LTE downlink. Additionally we show the extension to our proposed adaptive retransmission scheme using reliability metrics.

A. LTE uplink transmission scheme

In Fig. 1 the LTE uplink encoding principle is shown. A binary data sequence $\mathbf{a}_i \in \mathbb{F}_2^{N_\text{a}}$ with length N_a is encoded by a Turbo encoder into a codeword sequence $\mathbf{b}_i \in \mathbb{F}_2^{N_\text{b}}$ of the ith transmission. This overall codeword has the mother code rate $R = N_\text{a}/N_\text{b} = 1/3$. Out of this codeword $\mathbf{b}_i$, the rate matching block selects a number of bits depending on the redundancy version r and number of used physical resource block n_PRB to construct the codeword $\mathbf{c}_i^r \in \mathbb{F}_2^{N_\text{c}}$ with length N_c. This results to an overall effective code rate $R_\text{C} = \frac{N_\text{a}}{N_\text{c}}$. Note that the used physical resource blocks are always in the range between one and the maximum of the user specific scheduled physical resource blocks $1 \leq n_\text{PRB} \leq N_\text{PRB}^\text{max}$.

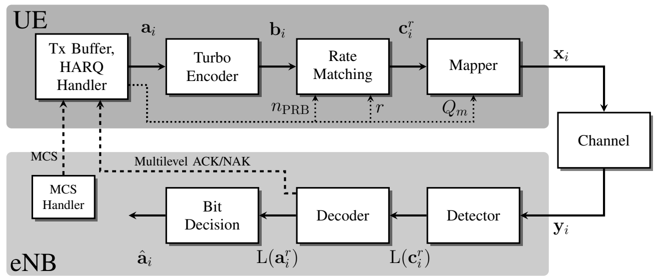

Fig. 1. HARQ transmission principle, exemplifies uplink, with an outer feedback loop (MCS) and an inner feedback loop (multilevel ACK/NAK)

The code bits $c_{i,\ell}$ of the codeword $\mathbf{c}_i$ with $\ell = 1, \ldots, N_\text{c}$ are mapped to symbols $x_{i,\kappa}$ of an M-ary modulation alphabet $\mathbb{X}$ (e.g. QPSK, 16-QAM) with modulation index $Q_m = \log_2(M)$ and are transmitted to the base station (evolved Node B (eNB)), with an overall (re-)transmission size of $N_\text{x}^{(i)} = N_\text{c}/Q_m$. As mentioned before, $N_\text{x} = f(n_\text{PRB}, Q_m)$ is dependent on the utilization of physical resources in terms of physical resource blocks n_PRB and configured in the rate matching block to configure the utilization and the modulation alphabet by Q_m. In case of a block flat fading channel the received signal vector is given by

$$\mathbf{y}_i = h_i \mathbf{x}_i + \mathbf{n}_i \ , \tag{1}$$

where $\mathbf{n}_i$ is a zero mean Gaussian noise vector with $\mathbf{n}_i \sim \mathcal{N}(0, \sigma_n^2)$. The coefficient h_i denotes a complex-valued zero-mean circular symmetric Gaussian distributed variable with variance one.

Based on the received symbol $y_{i,\kappa} \in \mathbf{y}_i$ and the channel coefficient h_i, we calculate the log-likelihood ratio $\text{L}(c_{i,\ell})$ of the participating coded bit $c_{i,\ell}$ like in [14]. These LLRs are then passed to the Turbo decoder, which delivers decoded LLR values for the information bits $\text{L}(a_{i,k})$. After a hard decision based on these LLRs a cyclic redundancy check (CRC) is done. If the CRC fails a NAK will be transmitted to UE to denote a decoding failure, otherwise an ACK is transmitted over the feedback link.

B. LTE uplink HARQ procedure

LTE uplink provides adaption techniques to adapt the actual transmission parameters to the link quality, which can be separated into an outer and an inner Link Adaptation (LA), refer to Fig. 1. In the outer loop the base station (eNB) informs the user equipment (UE) which modulation coding scheme (MCS) is selected to satisfy a maximum block error rate requirement. To determine the MCS, the eNB measures UL SNR based on pilot sequences. If the decoding fails in one HARQ transmission the inner LA is used, which is based on a simple ACK/NAK feedback. Here, link adaptation is implemented by using Incremental Redundancy (IR) [15]. The IR selection of the code bits $c_{i,\kappa}^r$ is described in [16]. If a NAK is received at the UE, the redundancy version r is changed and another codeword $\mathbf{c}_i^r$ is selected. Note by using only a simple NAK, without UL grant, the (re)transmission size $N_\text{x}^{(i)}$ and modulation alphabet Q_m stays the same within one HARQ transmission in LTE.

In contrast to a fixed IR scheme, this paper focuses on an adaptive retransmission scheme which configures the retransmission size in the inner loop by using a reliability based approach. The HARQ handler in Fig. 1 determines the new retransmission size $N_\text{x}^{(i)}$ based on the received multilevel ACK/NAK.

III. Feedback schemes

In this section, we illustrate the idea of adaptive retransmission sizes in case of a decoding error. For that, two different approaches are proposed. In the first approach we try to predict the size of the next retransmission in terms of effective SNR measurements, based on ACMI. The other approach is based on the decoding success of the Turbo decoder. Here, the prediction of the size of the next retransmission is based on the output of the decoder. Note that the eNB predicts the new retransmission size in terms of number of physical resource blocks $n_\text{PRB}^{(i+1)}$.

A. SNR based feedback

The probability of a decoding error in one HARQ process after the i^th transmission is given by the outage probability

$$P_\text{out}(R_1) = \text{Prob}(\text{ACMI}(\mathbf{SNR}, i) \leq R_1) \tag{2}$$

given in [9] and [15], where $R_1 = Q_m R_\text{C}$ is the target rate per symbol of the first transmission. The vector $\mathbf{SNR} \in \mathbb{R}^i$ is composed of all effective SNRs of the transmission. $\text{ACMI}(\cdot)$ gives the accumulated mutual information (ACMI) and can be calculated as described in [9] by using channel capacity $C(\cdot)$:

$$\text{ACMI}_\text{IR}(\mathbf{SNR}, i) = \sum_{j=1}^{i} \frac{N_\text{x}^{(j)}}{N_\text{x}^{(1)}} C\left(\text{SNR}_j\right), \tag{3}$$

where $N_\text{x}^{(j)}$ is the size of the j^th transmission. With (2) and (3) the $(i+1)^\text{th}$ transmission can be correctly decoded if

$$N_\text{x}^{(i+1)} C(\text{SNR}_{i+1}) > N_\text{x}^{(1)} R_1 - \sum_{j=1}^{i} N_\text{x}^{(j)} C(\text{SNR}_j) \tag{4}$$

is fulfilled. At time instance i, the eNB has no information of the effective SNR_{i+1} of the next transmission. Hence, the eNB estimates the new transmission size $N_\text{x}^{(i+1)}$ based on the mean SNR of the last transmissions. The selection of the next retransmission size is done by searching $n_\text{PRB}^{(i+1)}$ which fulfills the condition

$$n_\text{PRB}^{(i+1)} = \left\lceil \frac{N_\text{x}^{(i+1)}}{N_\text{x}^{(1)}} N_\text{PRB}^\text{max} \right\rceil . \tag{5}$$

Here, the next retransmission size $N_\text{x}^{(i+1)}$ based on (4) is normalized with the length $N_\text{x}^{(1)}$ of the first transmission, this gives a portion of needed physical resource blocks. *Note:* The retransmission size is chosen with minimum $n_\text{PRB}^{(i+1)} = 1$ and maximum $n_\text{PRB}^{(i+1)} = N_\text{PRB}^\text{max}$.

B. Bit error probability based feedback

The LLRs given by $\text{L}(a_{i,k})$ at the decoder output deliver a reliability information of the info bit $a_{i,k}$. These values can be used to exactly calculate the bit error probability (BEP) $P_{b,k}$ for every bit, by c.f. [8]:

$$P_{b,k} = \text{P}(\hat{a}_{i,k} \neq a_{i,k} | \mathbf{y}) = \frac{1}{1 + e^{|\text{L}(\hat{a}_{i,k})|}}. \tag{6}$$

Using the bit error probabilities of $P_{b,k}$, the average bit error probability of the information word is given by

$$P_b = \frac{1}{N_\text{a}} \sum_{k=1}^{N_\text{a}} \frac{1}{1 + e^{|\text{L}(\hat{a}_{i,k})|}}. \tag{7}$$

The eNB selects a number of resource blocks $n_\text{PRB}^{(i+1)}$ which adapt the physical resources to the actual decoding success in the next $i+1$ transmission based on the bit error probability P_b using

$$n_{\mathrm{PRB}}^{(i+1)} = \left\lceil \frac{P_b}{0.5} N_{\mathrm{PRB}}^{\max} \right\rceil . \tag{8}$$

By normalizing the bit error probability, we get directly a linear mapping of the bit error probability $0 \leq P_b \leq 0.5$ to the next retransmission size $n_{\mathrm{PRB}}^{(i+1)}$ in terms of physical resource blocks. Nonlinear or MCS dependent mappings are possible, but in this paper we focus on the linear mapping in (8).

1) Reduced Feedback 2 bit: To reduce the overhead of the feedback, we focus on a 2 bit ACK/NAK message. Depending on the SNR and BEP approach, the eNB chooses an ACK in case of no retransmission and a NAK_1 to NAK_3 for a short, medium and long retransmission size, respectively. Every NAK_ν gets a specific number of physical resource blocks $n_{\mathrm{PRB},\nu}^{(i+1)} \leq N_{\mathrm{PRB}}$ which are used in the next retransmission.

In a realistic system ACK and NAK get distorted within a transmission over the channel. As introduced, the NAKs determine the size of a retransmission packet. For that reason, an ACK to NAK_3 error adds more redundancy than an ACK to NAK_1 error.

Assigning the following mapping: ACK = $[0\ 0], \mathrm{NAK}_1 = [0\ 1], \mathrm{NAK}_2 = [1\ 0], \mathrm{NAK}_3 = [1\ 1]$, we minimize the error probability of ACK to NAK_3 and vice versa, due to the maximum hamming distance. Note that we determine the bitwise error probability of an ACK and NAK is p_{ACK} and p_{NAK}.

IV. Performance Analysis

In this section, we present the simulation results in an LTE link-level uplink simulator chain. As key performance indicator the average throughput performance defined by

$$\eta = \frac{\text{number of correctly decoded bits}}{\text{number of transmitted bits}} \tag{9}$$

and the delay between receiving and decoding success of one packet is used, which is defined by 8ms steps due to the synchronous HARQ process.

A. Simulation setup

We use a single user point-to-point communication with simulation parameters setup summarized in Table I. We focus on a 5 MHz bandwidth scenario, which uses $N_{\mathrm{PRB}}^{\max} = 25$ physical resource blocks and the user is assigned to the full bandwidth in the first transmission. Each of these resource blocks contain 12 sub-carriers with a sub-carrier spacing of 15 kHz. Table II gives additional information on the modulation and coding schemes. Note that the principle of using multilevel ACK/NAK can be easily extended to other bandwidths. In the simulations, we focus on two different channel types, namely the Vehicular A with a UE speed of 30 km/h (VEHA30) and a Typical Urban scenario with a UE speed of 3 km/h (TU3).

It should be noted, that the results are worked out in a link level simulator including realistic impairments, like channel estimation, SNR estimation, Turbo encoding scheme defined in [16] etc..

TABLE I
System parameters for LTE link-level uplink simulation chain

Parameters	Setup
Carrier frequency	2.3 GHz
Bandwidth	5 MHz
Physical Resource Blocks $N_{\mathrm{PRB}}^{\max}$	25
Modulation and Coding	see Table II
Turbo code rate	1/3
Channel	TU3: Typical Urban, 3 km/h [17]
	VEHA30: Vehicular A, 30 km/h [18]
Max. number of retransmissions	9

TABLE II
Modulation and Coding schemes

MCS	Q_m	N_{a}	N_{c}	N_{PRB}	R_{C}
0,...,6	2 (QPSK)	928,...,4416	7200	25	0.13,...,0.62
7,...,15	4 (16QAM)	4992,...,10752	14400	25	0.35,...,0.75

B. Performance of Outer Loop Link Adaption

Fig. 2 shows the throughput performance of different MCSs out of Table II by using the VEHA30 channel without any retransmission. Out of this measurement, we store a lookup table (LUT) which gives us switching points of the MCS which the UE should use to fulfill a given target block error rate $\mathrm{BLER}_{\mathrm{target}}$ for the first transmission at a specific SNR. For that, the selected MCS is a function of the estimated SNR at eNB and a given $\mathrm{BLER}_{\mathrm{target}}$, like $\mathrm{MCS} = f(\mathrm{SNR}_i, \mathrm{BLER}_{\mathrm{target}})$. The UE configures the next transmission by using the signaled MCS. We assume an MCS decision delay of 6 ms. Using this outer loop LA, the throughput performance of an LTE system with fixed size retransmission is shown in Fig. 3. As comparison the envelope of Fig. 2 is also presented, additionally a conservative LA with $\mathrm{BLER}_{\mathrm{target}} = 0.1$ and a more aggressive LA with $\mathrm{BLER}_{\mathrm{target}} = 0.9$ are shown. In terms of throughput performance η the aggressive LA outperforms the conservative LA, due to a better utilization of the channel at costs of transmission delay (see also Fig. 6).

C. Inner Loop Link Adaption

In the previous subsection, the focus was on outer LA with fixed size retransmission using single ACK/NAK. In this section, we focus on the adaption of our proposed retransmission size using inner link adaption by the BEP and SNR approaches. Motivated by Fig. 3 we use $\mathrm{BLER}_{\mathrm{target}} = 0.9$ LA. In our simulations, we have $N_{\mathrm{PRB}} = 25$ different physical resource blocks, due to the bandwidth of 5 MHz. Among the 25 available PRB we choose $n_{\mathrm{PRB},1}^{(i+1)} = 5$, $n_{\mathrm{PRB},2}^{(i+1)} = 14$ and $n_{\mathrm{PRB},3}^{(i+1)} = 21$ to be the retransmission sizes of NAK_1, NAK_2 and NAK_3, respectively. It is also possible to choose other mappings. This is a trade-off between delay and throughput.

Fig. 4 shows the throughput performance of the approaches introduced in Section III. Here the BEP and SNR approach with full $n_{\mathrm{PRB}}^{(i+1)}$ resolution as well as for reduced feedback is presented. The adaptive approaches have better throughput performance than the LTE scenario with fixed size retransmission. The adaptive approaches gain up to 30% at an SNR of 14 dB. BEP slightly outperforms the SNR approach with a gain of throughput of around 5%. Due to the estimation

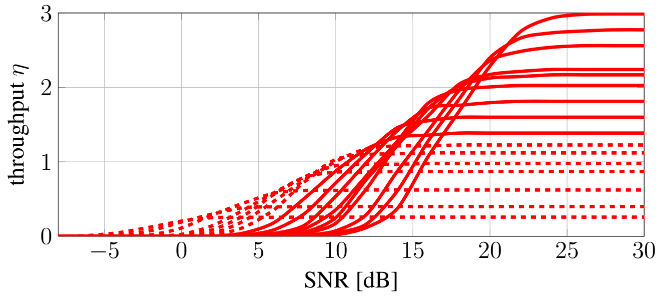

Fig. 2. Throughput performance curves: dashed for QPSK (MCS = $0, \ldots, 6$) and solid for 16QAM (MCS = $7, \ldots, 15$)

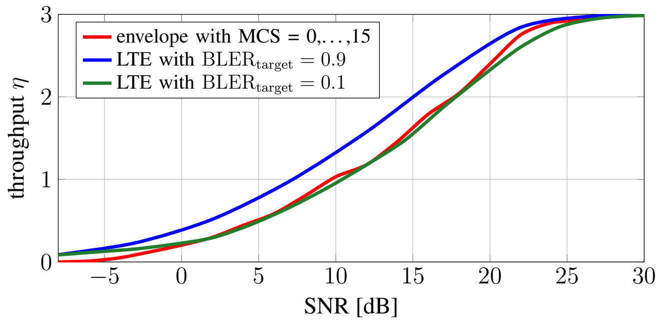

Fig. 3. Link adaptation with a conservative and a aggressive BLER$_{\text{target}}$ with single bit ACK/NAK, in contrast to the envelope of Fig. 2.

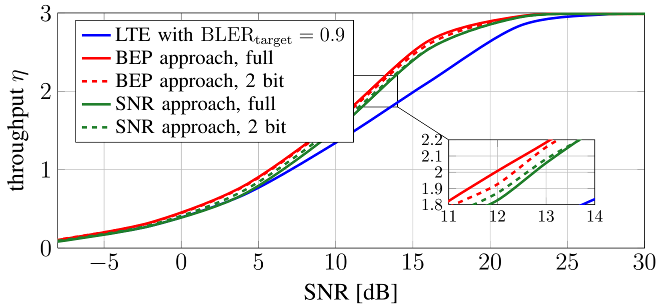

Fig. 4. Throughput performance curves using reliable information as feedback with a Vehicular A channel, UE speed of 30 km/h (see Table I).

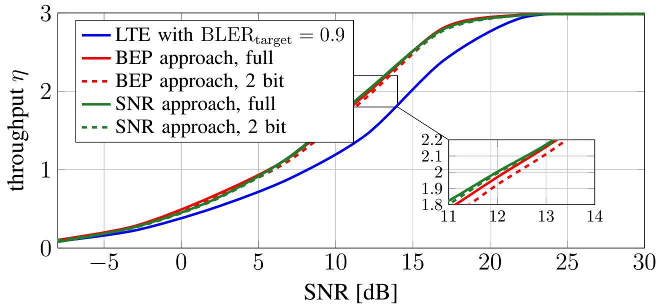

Fig. 5. Throughput performance curves using reliable information as feedback with a Typical Urban channel, UE speed of 3 km/h (see Table I)

of the SNRs the next retransmission size $N_{\text{x}}^{(i+1)}$ is predicted with equation (4). If an SNR value is estimated with an error the next retransmission size $N_{\text{x}}^{(i+1)}$ could be negative, which leads to a $n_{\text{PRB}}^{(i+1)} = 1$, but the needed retransmission size could be larger. In contrast to that, the BEP approach takes also the decoding procedure into account and the resulting bit error probability in (7) is always between $0 \leq P_b \leq 0.5$. For that it contains inherent more information of the overall transmission procedure than the SNR approach. This leads to a more robust system. The 2 bit ACK/NAK systems have almost the same throughput performance than their full resolution counterparts. As previously mentioned, the SNR approach calculates sometimes negative retransmission sizes due to wrongly estimated SNR values. In contrast to that the 2 bit ACK/NAK scheme has a slightly better performance than the full resolution scheme. Fig. 5 shows the throughput performance of the same approaches for a TU3 channel scenario. This channel only provides a small variation, due to the low UE speed. The estimation of the SNRs is more accurate and therefore the prediction of the SNR$_{i+1}$ is more precise. For this channel the approaches have de facto the same performance and outperform the LTE HARQ system with around 37% throughput at 14 dB.

The cumulative distributed function of decoding delay is shown in Fig. 6. The blue curves show the LTE uplink with single ACK/NAK. As expected, the BLER$_{\text{target}} = 0.9$ has a higher delay until decoding success, due to the more aggressive strategy, introduced in Subsection IV-B. In case of the VEHA30 channel, we can directly read off the 10% decoding error after the first transmission in the BLER$_{\text{target}} = 0.1$ case. This behavior is not observed in all the other cases, due to the limited number of MCS (see Table II). As we can see, the BEP and SNR approach also insert a delay to the decoding success. At an SNR of 14dB (@VEHA30 and @TU3) around 10% of the transmissions have a higher delay in comparison to the fixed LTE uplink using BLER$_{\text{target}} = 0.9$. At 5dB the BEP approach outperforms the SNR approach, due to the better prediction of the needed channel utilization by around 10% transmissions with better delay performance in the VEHA30 5dB case. The estimation of the SNRs is more accurate in the slower changing TU3 5dB case. For that, the BEP approach performs similar to the SNR approach.

Considering the throughput and the delay, it can be observed that when using 2 bit ACK/NAK instead of single bit ACK/NAK the throughput performance increases at the costs of delay. In other words, by using reliability information the throughput performance gets better if the system accepts more delay, due to the possible adapting of the channel condition and decoding success.

D. Erroneous ACK/NAK

Fig. 7, 8 show the throughput performance and the cdf of the delay of the different reliability approaches and the fixed LTE uplink scheme assuming an unreliable feedback link, respectively. Here, different asymmetric bitwise error probabilities p_{ACK} and p_{NAK} are shown. We focus on small ACK errors probability with p_{ACK} equal to 0.01 and 0.02 and larger NAK error probability $p_{\text{NAK}} = 0.05$.

As expected, the performance of the erroneous schemes have a small throughput degradation. At high SNR, the degradation is dominated by the error probability of ACK p_{ACK}. In the medium SNR range the occurrence of a NAK is higher,

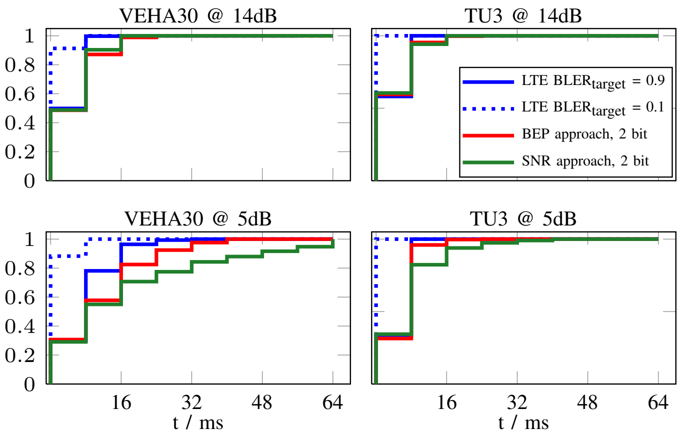

Fig. 6. Cumulative distribution function of delay until decoding success of a packet. Here, solid lines use $\text{BLER}_{\text{target}} = 0.9$.

but the overall behavior stays similar with only a marginal performance loss. The overall delay performance stays the same, with only marginal differences, as depicted in Fig. 8.

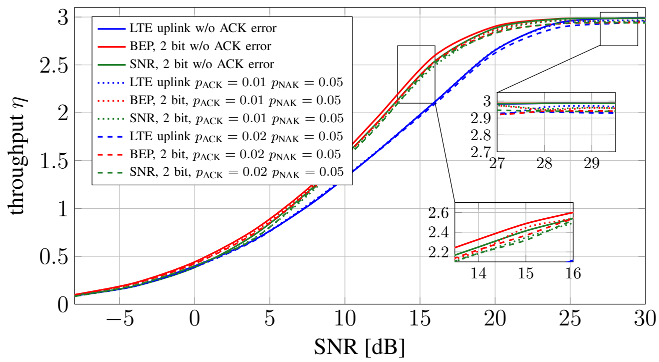

Fig. 7. Throughput performance curves with VEHA30 channel and erroneous ACK/NAK signaling.

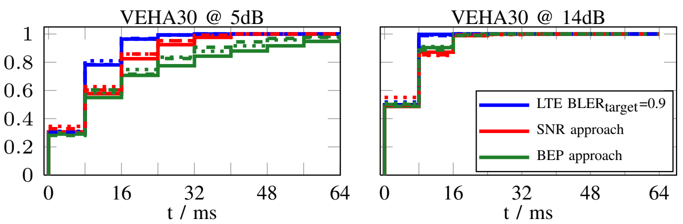

Fig. 8. Cumulative distribution function of delay until decoding success of a packet. Here, solid lines without any feedback error, dotted lines with feedback errors ($p_{\text{ACK}} = 0.01$, $p_{\text{NAK}} = 0.05$) and dashed lines with use ($p_{\text{ACK}} = 0.02$, $p_{\text{NAK}} = 0.05$)

V. Conclusion

We investigated the throughput performance of reliability-based HARQ using two different approaches, which adapt the size of a retransmission in case of a decoding error. Here a single user point-to-point HARQ LTE uplink is assessed, but similar results are expected in the LTE downlink. We further analyzed the impact of a realistic link-level simulation in terms of estimation errors of parameters in different channel scenarios. Here the BEP approach has shown to be more robust against estimation errors than the SNR approach due to the inclusion of reliability information of the decoder output. Both approaches gain up to 37% in terms of throughput performance in comparison to the LTE uplink with full size retransmissions. This behavior is also observed with a marginal performance loss by reducing the possible number of retransmission sizes and by introducing a simple extension to a two bit ACK/NAK feedback. Further improvements are possible by considering other nonlinear mappings of the BEP or the number of the retransmission sizes. All these results come by the expense of delay of decoding success. Hence, reliability-based HARQ can improve the throughput performance in delay insensitive schemes such as streaming and background downloads.

References

[1] J.M. Shea, "Reliability-based Hybrid ARQ," *Electronics Letters*, vol. 38, no. 13, pp. 644–645, 2002.

[2] A. Roongta and J.M. Shea, "Reliability-based Hybrid ARQ using Convolutional Codes," in *Communications, 2003. ICC '03. IEEE International Conference on*, 2003, vol. 4, pp. 2889–2893 vol.4.

[3] A. Roongta and J.M. Shea, "Reliability-based Hybrid ARQ and Rate-compatible Punctured Convolutional (RCPC) Codes," in *Wireless Communications and Networking Conference, 2004. WCNC. 2004 IEEE*, 2004, vol. 4, pp. 2105–2109 Vol.4.

[4] A.R. Raghavan and C.W. Baum, "A Reliability output Viterbi Algorithm with Applications to Hybrid ARQ," *Information Theory, IEEE Transactions on*, vol. 44, no. 3, pp. 1214–1216, 1998.

[5] C. Berrou, A. Glavieux, and P: Thitimajshima, "Near Shannon Limit Error-correcting Coding and Decoding: Turbo-codes. 1," in *IEEE International Conference on Communications (ICC93)*, New York, May 1993, vol. 2, pp. 1064–1070.

[6] V. Tripathi, E. Visotsky, R. Peterson, and M. Honig, "Reliability-based Type II Hybrid ARQ Schemes," in *Communications, 2003. ICC '03. IEEE International Conference on*, 2003, vol. 4, pp. 2899–2903 vol.4.

[7] E. Visotsky, Yakun Sun, V. Tripathi, M.L. Honig, and R. Peterson, "Reliability-based Incremental Redundancy with Convolutional Codes," *Communications, IEEE Transactions on*, vol. 53, no. 6, pp. 987–997, 2005.

[8] J.C. Fricke and P.A. Hoeher, "Reliability-based Retransmission Criteria for Hybrid ARQ," *Communications, IEEE Transactions on*, vol. 57, no. 8, pp. 2181–2184, 2009.

[9] Jung-Fu Cheng, Y.-P.E. Wang, and S. Parkvall, "Adaptive Incremental Redundancy [WCDMA Systems]," in *Vehicular Technology Conference, 2003. VTC 2003-Fall. 2003 IEEE 58th*, 2003, vol. 2, pp. 737–741 Vol.2.

[10] Jung-Fu Cheng, "Coding Performance of Hybrid ARQ Schemes," *Communications, IEEE Transactions on*, vol. 54, no. 6, pp. 1017–1029, 2006.

[11] E. Uhlemann and L.K. Rasmussen, "Analytical Approach for Maximizing the Average Code Rate of Incremental Redundancy Schemes," in *Communications, 2005 Asia-Pacific Conference on*, 2005, pp. 481–485.

[12] G. Caire and D. Tuninetti, "The Throughput of Hybrid-ARQ Protocols for the Gaussian Collision Channel," *Information Theory, IEEE Transactions on*, vol. 47, no. 5, pp. 1971–1988, 2001.

[13] Younghoon Whang and Seung-Hoon Hwang, "Multilevel Control Signaling for Hybrid ARQ," in *Wireless Communications, Networking and Mobile Computing, 2008. WiCOM '08. 4th International Conference on*, 2008, pp. 1–3.

[14] M. Woltering, D. Wübben, A. Dekorsy, V. Braun, and U. Doetsch, "Performance of HARQ with Reduced Size Retransmissions using Network Coding Principles," in *IEEE 77th Vehicular Technology Conference (VTC2013-Spring)*, Dresden, Germany, Jun 2013.

[15] Jung-Fu Cheng, "On the Coding Gain of Incremental Redundancy over Chase Combining," in *IEEE Global Telecommunications Conference, 2003. (GLOBECOM03)*, Dec. 2003.

[16] 3GPP TS 36.212 V9.2.0, "Multiplexing and Channel Coding," Jun. 2010.

[17] 3GPP TR 25.943 V11.0.0, "Deployment Aspects," Sept. 2012.

[18] UMTS 30.03 version 3.2.0, "Selection Procedures for the Choice of Radio Transmission Technologies of the UMTS," April. 1998.