Influence of HARQ with Unreliable Feedback on the Throughput of UMTS LTE

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***Abstract*—In this paper, the impact of HARQ signaling errors caused by unreliable feedback on the throughput of communication systems like UMTS LTE is investigated. We derive analytical expressions for the calculation of the average number of transmissions per data frame as well as the system throughput based on a general feedback channel model. In combination with the residual *frame error rates* (FERs) after channel decoding, measured for a system with error-free feedback, a semi-analytical evaluation of the influence of unreliable feedback information on the system throughput can be carried out for any feedback channel condition. Consequently, time-consuming simulations of the respective system with unreliable feedback can be avoided. The theoretical results are verified by extensive simulations of the UMTS LTE physical layer. They are also applicable to other communication systems.**

***Index Terms*—LTE, HARQ, Signaling Errors.**

I. Introduction

In modern wireless and mobile communication systems, *Hybrid Automatic Repeat reQuest* (HARQ) schemes are employed [1] to reduce the effect of channel degradations on the system performance. Additional transmissions are requested by the receiver based on a *cyclic redundancy check* (CRC). The corresponding signaling is carried out over a feedback channel by means of *acknowledgments* (ACK) and *negative acknowledgments* (NACK). In the first case the transmitter proceeds with the transmission of new frames while in the latter case incremental *redundancy versions* (RVs) of the same frame are transmitted which can be exploited at the receiver as additional soft information.

The influence of HARQ schemes on the system performance has mostly been studied for reliable feedback channels without feedback errors, e.g. in [2], [3], [4]. In general, this cannot be assumed. In [5] the impact of signaling errors on the throughput of *high speed uplink packet access* (HSUPA) is verified by simulations. In [6], the coverage of LTE is improved by reducing the impact of ACK/NACK signaling errors using a technique which is called TTI bundling. However, there are only a limited number of contributions which examine analytically the impact of unreliable ACK/NACK feedback. In most of the publications, the analysis is done for special protocols or channel models. In [7], [8] for example, the performance of the ARQ Go-Back-N protocol and in [9], [10] the effectiveness of the selective repeat protocol in Markov channels is analyzed under the assumption of unreliable feedback. The impact of noisy feedback on various types of HARQ schemes is discussed in detail for block fading channels in [11], [12], [13], [14], [15]. In most contributions, it is further assumed that NACK-ACK errors can be detected by a CRC and thus be avoided by the considered communication system. However, this might not be the case in a real mobile communication system such as, e.g., in HSPA [16] in which error handling strategies are formulated for ACK-NACK as well as NACK-ACK errors. Furthermore, the probability of both error types does not have to be identical as it is stated in [6] where different target error rates based on the 3GPP recommendations are given for the transmission of ACKs and NACKs, respectively.

Therefore, we will provide a more general analysis of such systems with unreliable feedback:

- We will abstract from the considered communication channel and the employed HARQ protocol, respectively.
- No restrictions are made for the error handling of ACK/NACK signaling errors, i.e., NACK-ACK errors are included into the analysis.
- Expressions for the required number of transmissions per frame and the resulting overall system throughput are derived analytically in dependency of the residual *frame error rates* (FERs) and the current quality of the feedback channel.
- Links to specific but relevant cases are given which can be covered by our general analysis.

Based on the residual frame error rates of the communications system with reliable feedback, the influence of signaling errors can now be evaluated analytically supporting the design of feedback transmission schemes (e.g., required code rate, transmission power). Time-consuming simulations of the respective system with unreliable feedback can thus be avoided. The correctness and the benefit of the presented analysis is verified by extensive UMTS LTE physical layer simulations.

II. LTE System Model

The considered LTE transceiver (see Fig. 1) is implemented according to the physical layer specifications of the LTE standard [17]. 24 cyclic redundancy check (CRC) bits are appended to a frame of $l_u = 6120$ data bits $\underline{u}$ (maximum data frame size in LTE systems [1]) which is then encoded by a systematic rate-$1/3$ turbo coder consisting of two parallel concatenated convolutional codes (PCCC) with octal generator polynomial $G = \{1, 15/13\}_8$ each generating one parity bit per data bit. For a given number l_u of data bits, a frame of l_x encoded bits $\underline{x}$ is selected for transmission by rate matching resulting in an effective code rate $r = l_u/l_x$. A frame size $l_x < 3\,l_u$ results in a code rate $r > 1/3$, whereas if l_x is sufficiently large, the code rate can take

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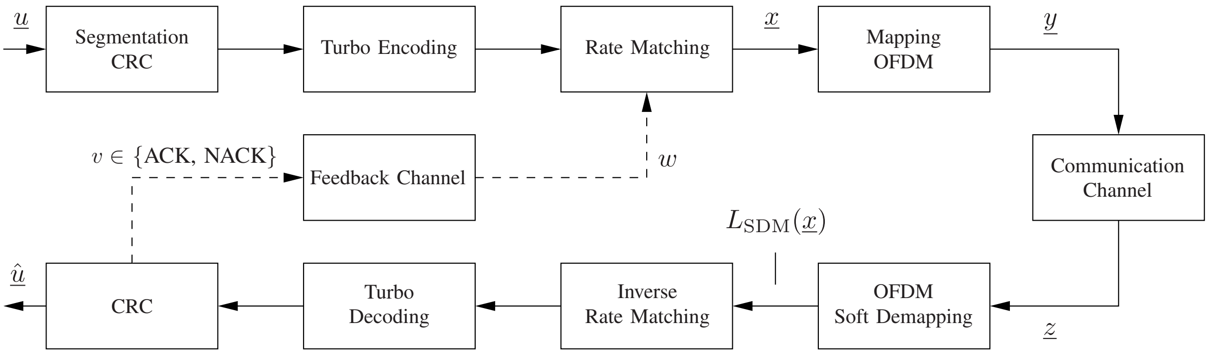

Figure 1. System model of the UMTS LTE physical layer.

values $r < 1/3$. The UMTS LTE HARQ scheme allows for up to $K = 4$ transmissions of different combinations of systematic and parity bits, the so-called redundancy versions (RVs). Obviously, each RV transmission implicitly decreases the effective code rate and results in losses in throughput and latency.

The bits selected for transmission are grouped to vectors of I_m bits with $I_m \in \{2, 4, 6\}$ with $m \in \{0, \ldots, M-1\}$ representing the M subcarriers of the OFDM system. The grouped bits are then assigned to complex modulation symbols (QPSK, 16QAM or 64QAM, all with Gray mapping) and OFDM modulated. A *cyclic prefix* (CP) is added to form the transmit signal $\underline{y}$.

At the receiving side the CP is removed and OFDM demodulation is performed. The demodulated complex symbols are fed to a *soft demapper* (SDM) which delivers reliability information in form of *a posteriori log-likelihood ratios* (LLR) $L_{\mathrm{SDM}}(\underline{x})$ on the encoded bits $\underline{x}$. The LLRs are then passed on to the PCCC turbo decoder consisting of two *soft input soft output* (SISO) channel decoders using the LogMAP algorithm [18]. After a fixed number of decoding iterations n_{Turbo} the data frame $\hat{\underline{u}}$ is hard decided from the resulting LLRs. CRC is performed and, in case of failure, an additional transmission is requested by sending a NACK to the transmitter. Otherwise an ACK is transmitted.

III. System Throughput with Unreliable Feedback

In most evaluations regarding the system throughput of wireless or mobile communication systems with HARQ, a perfect feedback channel for the transmission of ACK/NACK frames is assumed. However, in wireless systems various impairments on the physical link reduce the reliability of the feedback transmission. A general model for such an unreliable feedback channel which covers ACK-NACK as well as NACK-ACK signaling errors is depicted in Fig. 2. This model is defined by two conditional error probabilities $P_A = \mathrm{Prob}\{\mathcal{W}_i = \mathrm{NACK}|\mathcal{V}_i = \mathrm{ACK}\}$ and $P_N = \mathrm{Prob}\{\mathcal{W}_i = \mathrm{ACK}|\mathcal{V}_i = \mathrm{NACK}\}$ with $0 \leq P_A, P_N \leq 1/2$ in which $\mathcal{V}_i$ and $\mathcal{W}_i$ signify random processes.[1] The first error probability denotes the probability that an ACK is transmitted after the i-th data transmission ($1 \leq i \leq K$) but received as a NACK while the latter probability indicates the

[1]For $P_A = P_N$ this model is equivalent to a binary symmetric channel.

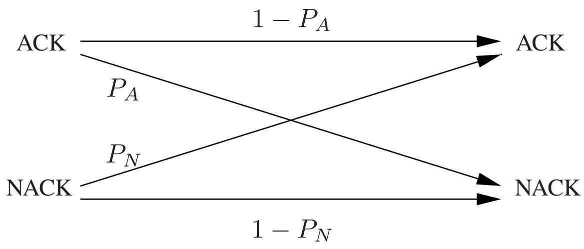

Figure 2. General model of the HARQ feedback channel.

opposite.[2] As stated in Sec. I P_A and P_N can be different in general. K is the maximum number of transmissions allowed by the system. Both probabilities P_A and P_N are independent of i since no HARQ is considered for the feedback channel. The state probabilities after the i-th data transmission are given by means of the residual FERs P_i of the communication system according to $\mathrm{Prob}\{\mathcal{V}_i = \mathrm{NACK}\} = P_i$ and $\mathrm{Prob}\{\mathcal{V}_i = \mathrm{ACK}\} = 1 - P_i$. Assuming code combining at the receiver the following constraint holds true:

$$1 \geq P_1 \geq P_2 \geq \ldots \geq P_K \geq 0. \tag{1}$$

Depending on the considered communication channel, P_i can either be determined by simulations or even by analytical derivation.

A measure for the performance of a communication system is its average throughput per channel use which is defined for a system with reliable feedback by

$$\mathcal{T}_K^{[\mathrm{r}]} = \frac{(1 - P_K) \cdot rI}{\overline{K}^{[\mathrm{r}]}}. \tag{2}$$

It depends on the code rate r, the number I of coded bits per modulation symbol (e.g., OFDM subcarrier), the average number of transmissions $\overline{K}^{[\mathrm{r}]}$ per frame and the residual error probability P_K after the K-th transmission. The factor $1 - P_K$ guarantees that, after the K-th transmission, only error-free decoded frames are considered for the calculation of $\mathcal{T}_K^{[\mathrm{r}]}$. Equation (2) can be adopted to a system with unreliable

[2]P_A and P_N are either predefined according to given target error rates (e.g. 3GPP recommendations) or chosen arbitrarily in order to determine those target error rates under the condition of a maximum tolerated loss in throughput.

feedback according to

$$\mathcal{T}_K^{[\mathrm{u}]} = C(K, P_N, P_i) \frac{(1 - P_K) \cdot rI}{\overline{K}^{[\mathrm{u}]}} \tag{3}$$

$$= C(K, P_N, P_i) \frac{\overline{K}^{[\mathrm{r}]}}{\overline{K}^{[\mathrm{u}]}} \mathcal{T}_K^{[\mathrm{r}]}, \tag{4}$$

where $C(K, P_N, P_i)$ is a correction term which incorporates the fact that NACK-ACK errors, in contrast to ACK-NACK errors, increase the residual FER after retransmission. $\overline{K}^{[\mathrm{u}]}$ is the average number of transmissions per frame and depends on the error probabilities P_A, P_N and P_i. Both terms will be derived in what follows. It is evident that $\mathcal{T}_K^{[\mathrm{u}]} = \mathcal{T}_K^{[\mathrm{r}]}$ for $P_A = P_N = 0$.

A. Average Number of Transmissions

In general, the average number of transmissions per frame $\overline{K}^{[\mathrm{u}]}$ is given by

$$\overline{K}^{[\mathrm{u}]} = \sum_{i=1}^{K} i \cdot P_{i|K}, \tag{5}$$

where $P_{i|K} = \mathrm{Prob}\{\mathcal{I} = i | \mathcal{K} = K\}$ denotes the probability that exactly i data transmissions are carried out under the condition that up to K transmissions are allowed by the system. For the probabilities $P_{i|K}$ it holds that

$$\sum_{i=1}^{K} P_{i|K} = 1. \tag{6}$$

These probabilities can be computed by means of the error probabilities P_A, P_N, P_i $(1 \le i \le K)$. For $K = 1$ the trivial solution is given by $P_{1|1} = 1$. For $K = 2$ there are 2 probabilities $P_{1|2}$ and $P_{2|2}$. Exactly 2 transmissions have to be carried out if either the first data transmission fails and the corresponding feedback does not fail or vice versa. In the rest of the cases exactly 1 transmission has to be performed. Consequently, the resulting probabilities are given by

$$P_{1|2} = 1 - P_{2|2} \tag{7}$$

$$\begin{aligned} P_{2|2} &= \mathrm{Prob}\{\mathcal{V}_1{=}\mathrm{ACK}\} \cdot \mathrm{Prob}\{\mathcal{W}_1{=}\mathrm{NACK}|\mathcal{V}_1{=}\mathrm{ACK}\} \\ &\quad + \mathrm{Prob}\{\mathcal{V}_1{=}\mathrm{NACK}\} \cdot \mathrm{Prob}\{\mathcal{W}_1{=}\mathrm{NACK}|\mathcal{V}_1{=}\mathrm{NACK}\} \\ &= (1 - P_1) P_A + P_1 (1 - P_N). \end{aligned} \tag{8}$$

If the number of allowed transmissions is increased to $K = 3$ the fraction of frames transmitted once does not change, i.e., $P_{1|3} = P_{1|2}$. With (6) the probability $P_{2|3}$ is given by $P_{2|3} = 1 - P_{1|3} - P_{3|3}$. Considering $P_{3|3}$, 3 scenarios are possible:

(1) Perfect decoding after the first transmission with probability $Q_1 = 1 - P_1$ and corrupted ACK feedback twice with probability P_A^2 results in the overall probability $(1 - P_1) P_A^2$ due to statistical independence.
(2) Faulty decoding after the second transmission with probability $Q_2 = P_2$ and error-free NACK feedback after the first and second transmission with probability $(1 - P_N)^2$ results in the overall probability $P_2 (1 - P_N)^2$.
(3) For the remaining fraction of packets Q_3, exactly two transmissions are required for perfect decoding with probability $Q_3 = 1 - Q_1 - Q_2 = 1 - (1 - P_1) - P_2 = P_1 - P_2$. In this case three transmissions are requested for error-free NACK feedback after the first transmission and corrupted ACK feedback after the second transmission resulting in the overall probability $(P_1 - P_2)(1 - P_N) P_A$.

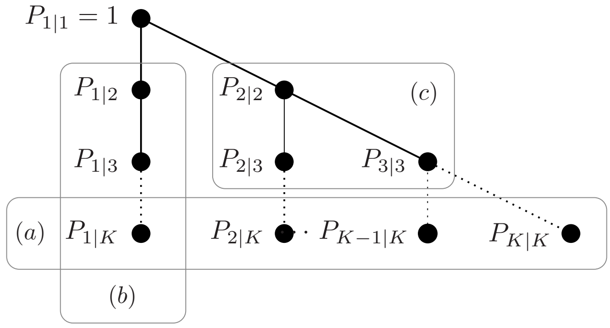

Figure 3. Tree-structure illustrating the computation rule for the average number of transmissions per frame.

Hence, the required probabilities for $K = 3$ transmissions can be summarized according to

$$P_{1|3} = P_{1|2} = 1 - P_{2|2} \tag{9}$$

$$P_{2|3} = 1 - P_{1|3} - P_{3|3} = P_{2|2} - P_{3|3} \tag{10}$$

$$\begin{aligned} P_{3|3} &= (1 - P_1) P_A^2 + (P_1 - P_2)(1 - P_N) P_A \\ &\quad + P_2 (1 - P_N)^2. \end{aligned} \tag{11}$$

Figure 3 visualizes how the required probabilities are split up with increasing K. Based on the previous considerations three major properties of the given tree structure are highlighted in Fig. 3 by gray boxes:

(a) $\displaystyle\sum_{i=1}^{K} P_{i|K} = 1 \quad \forall\, K$

(b) $P_{i|j} = P_{i|i+1} \quad \text{for} \quad i + 1 \le j \le K$

(c) $P_{i|i} = P_{i|i+1} + P_{i+1|i+1} \quad \text{for} \quad i \le K - 1$

For the example given above with $K = 3$ transmissions the properties (b) and (c) can be observed in (9) and (10), respectively. Based on these properties, the equation for the average number of transmissions $\overline{K}^{[\mathrm{u}]}$, as given in (5), can be simplified according to

$$\begin{aligned} \overline{K}^{[\mathrm{u}]} &= \sum_{i=1}^{K} i \cdot P_{i|K} = \sum_{i=1}^{K-1} i \cdot P_{i|K} + K P_{K|K} \\ &\overset{(b)}{=} \sum_{i=1}^{K-1} i \cdot P_{i|i+1} + K P_{K|K} \\ &\overset{(c)}{=} \sum_{i=1}^{K-1} i \left(P_{i|i} - P_{i+1|i+1} \right) + K P_{K|K} \\ &= \sum_{i=0}^{K-2} (i+1) P_{i+1|i+1} - \sum_{i=0}^{K-1} i \cdot P_{i+1|i+1} + K P_{K|K} \\ &= \sum_{i=0}^{K-2} P_{i+1|i+1} - (K-1) P_{K|K} + K P_{K|K} \\ &= \sum_{i=1}^{K} P_{i|i}. \end{aligned} \tag{12}$$

As a result of (12), it is sufficient to compute the probabilities $P_{i|i}$ rather than all of the probabilities corresponding to the tree structure depicted in Fig. 3. Accounting for the composition scheme of these probabilities revealed by (8) and (11), a direct computation rule can be formulated for any $i \leq K$:

$$P_{i|i} = \sum_{j=1}^{i-1} (P_{i-j-1} - P_{i-j})(1 - P_N)^{i-j-1} P_A^j + P_{i-1}(1 - P_N)^{i-1}, \quad P_0 = 1 \tag{13}$$

B. System Throughput

For a communication system with $P_N > 0$, the obtained throughput is reduced by a factor of $C(K, P_N, P_i)$ which is obviously independent of the error probability P_A. Some corrupted frames are not retransmitted during the HARQ process since the corresponding NACK feedback is corrupted as well. The probability of that scenario can be determined dependent on K and the error probabilities P_i and P_N:

(1) Probability of loosing a frame after the first transmission: $P_1 P_N$.
(2) Additional probability of loosing a frame only after the second transmission: $P_2 P_N (1 - P_N)$.
$(\cdot)$ Proceeds in the same manner.
(i) Additional probability of loosing a frame only after the i-th transmission: $P_i P_N (1 - P_N)^{i-1}$.

Based on the above considerations, it can be concluded that

$$C(K, P_N, P_i) = 1 - P_N \sum_{i=1}^{K-1} P_i \left(1 - P_N\right)^{i-1}. \tag{14}$$

Hence, the overall throughput for a communication system with unreliable feedback channel is given by means of (3), (12) and (14) according to

$$\begin{aligned} \mathcal{T}_K^{[u]} &= C(K, P_N, P_i) \frac{(1 - P_K) \cdot rI}{\overline{K}^{[u]}} \\ &= \left(1 - P_N \sum_{i=1}^{K-1} P_i \left(1 - P_N\right)^{i-1}\right) \frac{(1 - P_K) \cdot rI}{\sum_{i=1}^{K} P_{i|i}} \end{aligned} \tag{15}$$

with $P_{i|i}$ as derived in (13).

C. Link to Special Cases

Several special cases are covered by the expressions derived in the previous section illustrating the general nature of the underlying feedback channel model.

1. Reliable feedback channel according to [19], i.e., $P_A = P_N = 0$:

$$\overline{K}^{[u]} = \overline{K}^{[r]} = \sum_{i=1}^{K} P_{i|i} = 1 + \sum_{i=1}^{K-1} P_i \tag{16}$$

$$C(K, P_N, P_i) = 1. \tag{17}$$

The overall throughput is then given by

$$\mathcal{T}_K^{[u]} = \mathcal{T}_K^{[r]} = \frac{(1 - P_K) \cdot rI}{1 + \sum_{i=1}^{K-1} P_i}, \tag{18}$$

allowing the calculation of the throughput only based on FER measurements.

2. Perfect communication channel, i.e., $P_i = 0 \ \forall i$, and feedback channel with $0 \leq P_A, P_N \leq 1/2$:

$$\overline{K}^{[u]} = 1 + \sum_{i=1}^{K-1} P_A^i = \sum_{i=0}^{K-1} P_A^i = \frac{1 - P_A^K}{1 - P_A} \tag{19}$$

$$C(K, P_N, P_i) = 1. \tag{20}$$

For such a system, (15) simplifies to

$$\mathcal{T}_K^{[u]} = \frac{(1 - P_A) \cdot rI}{1 - P_A^K}. \tag{21}$$

3. Erasure feedback channel:
In most of the previous works the feedback channel is modeled as an erasure channel which is also covered by our general framework. It is often assumed that the ACK/NACK feedback is protected by, e.g., a CRC check. If an erasure occurs this information is always interpreted as a NACK which secures a cross over probability of $P_N = 0$. Applied to the general expressions given in (12), (13) and (15), this results in an average number of transmissions per frame of

$$\begin{aligned} \overline{K}^{[u]} &= \sum_{i=1}^{K} \left(\sum_{j=1}^{i-1} (P_{i-j-1} - P_{i-j}) P_A^j + P_{i-1} \right) \\ &= 1 + \sum_{i=1}^{K-1} P_i + \sum_{i=1}^{K-1} \left(P_A^i - P_i P_A^{K-i} \right) \end{aligned} \tag{22}$$

which is identical to the expression derived in [11].

IV. Analytical vs. Simulation Results

In order to evaluate the theoretical throughput of a communication system with unreliable feedback as given in (15), UMTS LTE as an exemplary physical layer has been simulated in an AWGN environment. Simulations were conducted with $n_{\text{Turbo}} = 10$ Turbo iterations, a maximum of $K = 4$ transmissions and with modulation and coding schemes as indicated in Table I. The residual FERs where simulated with an error-free feedback channel ($P_N = P_A = 0$). Based on these results the average number of transmissions and the system throughput can be calculated analytically with (12) and (15), respectively, for any feedback error probabilities P_A and P_N. The analytical results have been verified exemplarily by system simulations for P_N, $P_A \in \{0.1, 0.2\}$ and $P_N = P_A$.

Table I
Modulation and coding schemes.

Modulation	Code rates
QPSK ($I = 2$)	$r \in \{\frac{1}{6}, \frac{1}{5}, \frac{1}{4}, \frac{1}{3}, \frac{1}{2}, \frac{2}{3}, \frac{3}{4}\}$
16QAM ($I = 4$)	$r \in \{\frac{1}{2}, \frac{2}{3}, \frac{3}{4}, \frac{4}{5}\}$
64QAM ($I = 6$)	$r \in \{\frac{1}{2}, \frac{2}{3}, \frac{3}{4}, \frac{4}{5}\}$

Figure 4 shows the average number of transmissions of the UMTS LTE system, exemplarily for 16QAM ($I = 4$) with a code rate of $r = 4/5$. It can be seen that the number of necessary transmissions obviously decreases for an increasing channel quality. Additionally, a higher feedback error probability ($P_A = P_N > 0$) results in less average

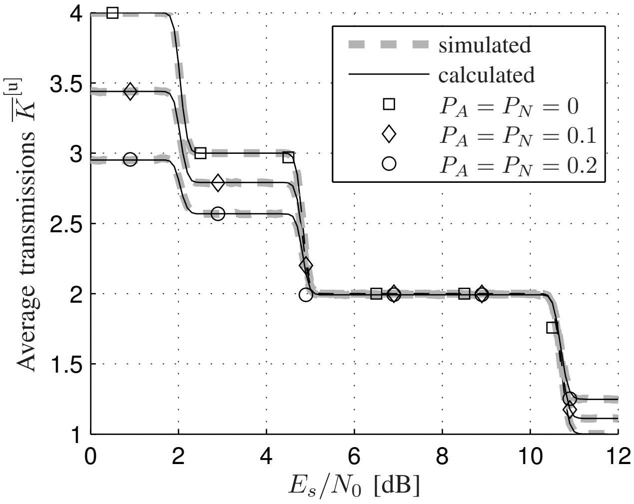

Figure 4. Average transmissions for $I = 4$ and $r = 4/5$.

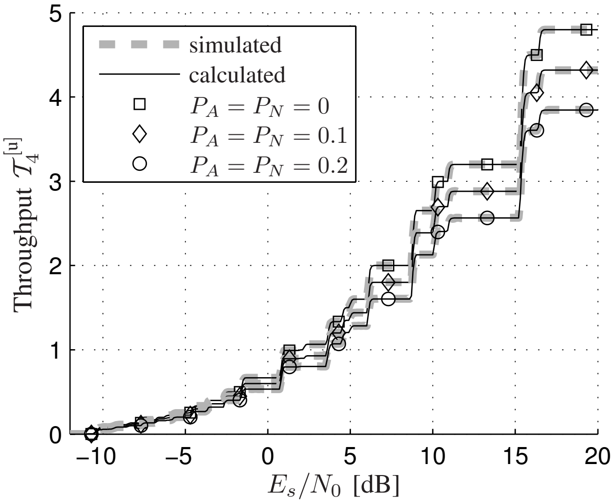

Figure 5. Throughput (envelope) for all modulation and coding schemes.

transmissions for low channel qualities. For high channel qualities ($P_i \to 0\,\forall i$) the average number of transmission converges corresponding to (19). Most importantly, it can be observed that the simulations match the analytical results perfectly, thus confirming the validity of our derivation.

In Figure 5 the envelope of the throughputs for all modulation and coding schemes is depicted. In case of unreliable feedback ($P_A = P_N > 0$) the curve progression is similar to error-free feedback, but the overall throughput decreases for higher feedback error probabilities. The perfect match of the simulated and the calculated throughput support the validity of our analytical evaluation as well. It is obvious that the simulation of a system with unreliable feedback channel is therefore superfluous, since the throughput can just be calculated analytically for any feedback error probabilities only based on the simulation of the system with reliable feedback.

V. Conclusion

In this contribution, HARQ with unreliable feedback has been studied analytically. We have defined a general feedback channel model which covers all possible feedback error scenarios. Based on this model, analytical expressions for the average number of transmissions and the overall system throughput in dependence of the feedback error probabilities have been derived and verified by extensive UMTS LTE simulations.

Conventionally, the adjustment of the feedback error probabilities results in a new simulation of the considered communication system. With the closed analytical solution presented in this paper, the influence of ACK/NACK signaling errors can be calculated avoiding those extensive time-consuming simulations since only the residual FERs of the system assuming no feedback errors are required. These derivations can further be useful for determining target feedback error rates under the condition of a maximum tolerated loss in system throughput.

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