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Published in:
2018 European Conference on Networks and Communications, EuCNC 2018

DOI:
10.1109/EuCNC.2018.8442537

Published: 20/08/2018

Document Version
Peer reviewed version

Please cite the original version:
Shariatmadari, H., Duan, R., Iraji, S., Jantti, R., Li, Z., & Uusitalo, M. A. (2018). Asymmetric ACK/NACK Detection for Ultra-Reliable Low-Latency Communications. In 2018 European Conference on Networks and Communications, EuCNC 2018 (pp. 162-166). [8442537] (European Conference on Networks and Communications). United States: Institute of Electrical and Electronics Engineers. https://doi.org/10.1109/EuCNC.2018.8442537

Asymmetric ACK/NACK Detection for Ultra-Reliable Low-Latency Communications

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***Abstract*—The fifth generation wireless systems are expected to encounter new services in order to provide connectivity for a wide range of applications. One of the considered services is ultra-reliable low-latency communications (URLLC), which has stringent requirements on availability, reliability, and latency. The communication efficiency of URLLC can be improved by employing error control protocols, such as automatic repeat request (ARQ) and hybrid ARQ (HARQ). However, this requires a reliable feedback channel to carry acknowledgement (ACK) and negative ACK (NACK) signals. Improving the detection reliability of ACK and NACK signals simultaneously entails allocating more resources for the feedback channel. Instead, we propose employing an asymmetric signal detection to provide a better protection for NACK signals compared to the ACK signals, without assigning more resources to the feedback channel. The simulation results show that the asymmetric signal detection can achieve a better resource utilization for URLLC.**

***Keywords*—5G, control channel, feedback, M2M, MTC, resource allocations, ultra-reliable low-latency communications.**

I. Introduction

The fifth generation (5G) wireless systems are expected to encounter new services in order to provide connectivity for a wide range of applications with different requirements. Ultra-reliable low-latency communications (URLLC) is one of the considered services that is essential for the realization of mission-critical applications, such as industrial Internet, tactile Internet, vehicular communications, and remote surgery [1]. URLLC has stringent requirements on availability, latency, and reliability [2], [3]. The third generation partnership project (3GPP) aims at providing reliable communications corresponding to the block error rate (BLER) of 10^{-5} with the radio latency of 1 millisecond (ms) for short size packets in the future cellular systems [4].

Generally, cellular systems employ error control protocols, such as automatic repeat request (ARQ) and hybrid ARQ (HARQ), in order to achieve high transmission rates while providing reliable communications. This is achieved by transmitting data incrementally, which requires utilizing a feedback channel in order to send either an acknowledgement (ACK) or a negative ACK (NACK) after each data reception. For URLLC, it is envisioned that the number of retransmission attempts should be limited, e.g., maximum of one retransmission attempt to meet the latency constraint [5]. It has been shown that employing HARQ scheme with only one retransmission attempt can improve the resource utilization of data channels significantly [6], [7].

In ARQ and HARQ schemes, a data recipient sends either an ACK or a NACK after each transmission/retransmission round to indicate the success or failure in decoding the message. In a simple case, a single bit is transmitted as the indication of ACK/NACK. In a more complex case, a multi-level ACK/NACK signals can be utilized [8]. For instance, reliability-based HARQ schemes enable the receiver to request data retransmission with different redundancy levels. This can further improve the communication efficiency, particularly, for delivering large size packets [9], [10], [11].

The feedback channel is prone to errors due to the noise and interference in the system, which can result in wrong detection of ACK/NACK signals [11]. Typical cellular systems, such as Long-Term Evolution (LTE), rely on higher layers to correct these kinds of errors [12]. However, URLLC cannot adopt this approach to resolve the feedback channel errors, due to the latency concern. Hence, novel techniques should be considered for designing the 5G systems in order to support URLLC efficiently [13]. For instance, the link adaptation can be applied taking into account the errors of data and feedback channels [7], [14].

In this paper, we consider the resource allocation approaches for an HARQ scheme with an imperfect feedback channel, carrying the ACK/NACK signals. The resource allocation strategies are analyzed according to the link qualities of both data and feedback channels, while satisfying the latency and reliability constraints. This approach allows employing asymmetric ACK/NACK signal detection, which enables providing a better protection for the NACK signal compared to the ACK signal. The simulation results show that the asymmetric signal detection can achieve a better communication efficiency compared to the conventional case in which both ACK/NACK signals have the same reliability.

The rest of this paper is organized as follows. Section II describes the considered system model and presents the error models for data and feedback channels. Section III formulates the optimization problem for the resource allocations. Section IV presents the simulation results. Finally, Section V concludes the paper.

II. System model

We consider a reliable communication scenario for downlink data transmissions in a cellular system, as shown in Fig.

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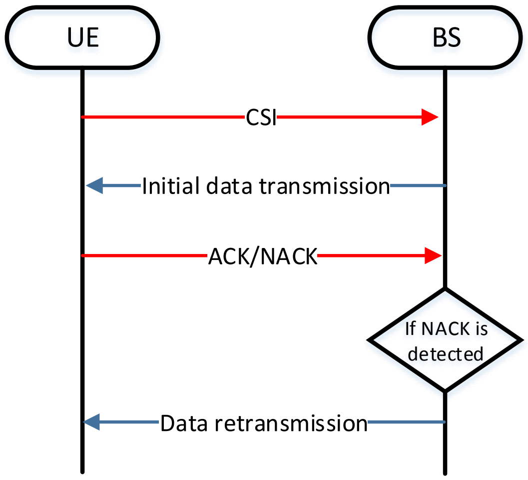

Fig. 1. The considered communication model.

1. A base station (BS) intends to deliver a message to a user equipment (UE). The BS can perform a maximum of two transmission rounds, i.e., only having one retransmission opportunity, for each message. This limitation is generally considered for both uplink and downlink transmissions in order to meet 0.5 ms in each direction according to the transmission time interval (TTI) of 0.125 ms, ensuring the overall 1 ms radio latency [4], [5].

The UE reports the downlink channel side information (CSI) to the BS before performing the downlink data transmissions. The CSI is carried over the uplink control channel. The CSI report is transmitted along the sounding reference signal (SRS) [15]. These allow the BS to estimate the qualities of both uplink and downlink. The BS utilizes these information for allocating the radio resource. The BS sends the initial encoded data part, while the receiver tries to decode the message. The UE sends ACK/NACK for indicating a success/failure in decoding the message. The ACK/NACK signals are represented by a single bit. In case the BS detects a NACK signal, it sends additional data information. The receiver then tries to decode the message utilizing all the received information. In this paper, we only consider the adaptive retransmission scheme, in which the initial transmission and retransmission rounds may have different data sizes [7].

The link qualities of uplink and downlink might be different as the BS and the UE are typically associated with different transmission powers. In addition, the uplink and downlink channel conditions might be quite different, particularly, in frequency division duplex (FDD) systems. We assume that the channel qualities remain the same during a single message transmission in both transmission directions. This means that the channel conditions for the initial data transmission and data retransmission are the same as the one that the UE reported to the BS. In addition, the ACK/NACK signals and CSI report experience the same channel condition.

To model the the reliability of data transmissions, we use the results of [16] and [17]. In particular, the achievable rate for a blocklength of n under a block error probability of ϵ is tightly approximated as

$$R^*(n,\epsilon,\gamma) = C(\gamma) - \sqrt{\frac{V(\gamma)}{n}}Q^{-1}(\epsilon) + \mathcal{O}\left(\frac{\log n}{n}\right), \quad (1)$$

where γ is the signal-to-noise ratio (SNR), $C(\gamma)$ is the Shannon capacity, and $V(\gamma)$ is the channel dispersion[1]. $Q(.)$ denotes the Gaussian Q-function and the notation $f(x) = \mathcal{O}(g(x))$ means that $\limsup_{x\to\infty} |f(x)/g(x)| < \infty$. For additive white Gaussian channel (AWGN), we have

$$C(\gamma) = \frac{1}{2}\log(1+\gamma),$$
$$V(\gamma) = \frac{\gamma}{2}\frac{\gamma+2}{(\gamma+1)^2}\log^2(e).$$

Using (1), the achievable BLER for delivering k bits of information[2] with n channel uses can be approximated by [7], [18]

$$E(n,k,\gamma) = Q\left(\frac{nC(\gamma)-k}{\sqrt{nV(\gamma)}}\right). \quad (2)$$

For ACK/NACK delivery, we assume that a one-bit message is carried over the control channel using binary phase shift keying (BPSK) modulation. The received feedback signal at the BS can be expressed as

$$y_f = h_f x + n, \quad (3)$$

where h_f is the channel coefficient known at the BS and $x \in \{+1/-1\}$ denotes ACK/NACK signals. The additive white Gaussian noise is modeled by $n \sim \mathcal{N}(0,\sigma^2)$. The SNR for the control channel can be expressed as $\gamma_f = |h_f|^2/\sigma^2$. Accordingly, the probability distribution of received signal is

$$p(y|s) = \frac{1}{\sqrt{2\pi\sigma^2}}e^{-\frac{(y-s)^2}{2\sigma^2}}, \quad (4)$$

where $s = +A = |h_f|$ if an ACK is transmitted and $s = -A = -|h_f|$ if a NACK is transmitted. The receiver needs to distinguish between the ACK and the NACK according to the received signal. For this purpose, the received signal is compared with a threshold ν. The signal is distinguished as the ACK if the $y > \nu$, otherwise as the NACK. There are two types of errors for the signal detection, i.e., the erroneous detection of ACK as NACK and the erroneous detection of NACK as ACK. Their associated probabilities can be expressed respectively as

$$P_{\mathsf{AN}} = \Pr(\text{NACK}|\text{ACK}) = \int_{-\infty}^{\nu} p(y|A)dy = Q\left(\frac{A-\nu}{\sigma}\right),$$
$$P_{\mathsf{NA}} = \Pr(\text{ACK}|\text{NACK}) = \int_{\nu}^{\infty} p(y|-A)dy = Q\left(\frac{A+\nu}{\sigma}\right).$$

Fig. 2 illustrates an example of wrong ACK/NACK detection. A symmetric signal detection can be utilized by setting the threshold $\nu = 0$ that results in having the same error probability for ACK/NACK, i.e., $P_{\mathsf{AN}} = P_{\mathsf{NA}}$. However, utilizing an asymmetric signal detection can provide a higher protection for NACK signal when $\nu > 0$, which results in $P_{\mathsf{AN}} > P_{\mathsf{NA}}$.

[1] It is a measure of the stochastic variability of the channel relative to a deterministic channel with the same capacity.

[2] The approximation is tight for $k \geq 100$.

be expressed as [7]

$$P_{\text{success}} = \big(1 - E(n_1, k, \gamma)\big) + E(n_1, k, \gamma)\big(1 - P_{\mathsf{NA}}\big) \times \left(1 - \frac{E(n_1 + n_2, k, \gamma)}{E(n_1, k, \gamma)}\right) = 1 - E(n_1, k, \gamma)P_{\mathsf{NA}} - E(n_1 + n_2, k, \gamma)(1 - P_{\mathsf{NA}}). \quad (6)$$

We assume that the overall communication reliability target is ρ for each message delivery. Hence, the remaining BLER after all transmission rounds is $\epsilon = 1 - \rho$. This target should be met regardless of the channel qualities of data and control channels. The resource allocation strategies can be obtained by minimizing the average channel uses over the data channel. The optimization problem can be formulated as

$$\underset{n_1, n_2, \nu}{\text{minimize}}\, \overline{N}, \qquad \text{subject to: } P_{\text{success}} \geq \rho, \quad (7)$$

where $\overline{N}$ is given in (5).

Deriving a closed form solution for this optimization problem is not tractable due to the existence of Q-function in $E(n, k, \gamma)$, P_{AN}, and P_{NA}. However, the optimal values can be derived through exhaustive search or can be approximated with the aid of coordinate descent algorithms [19].

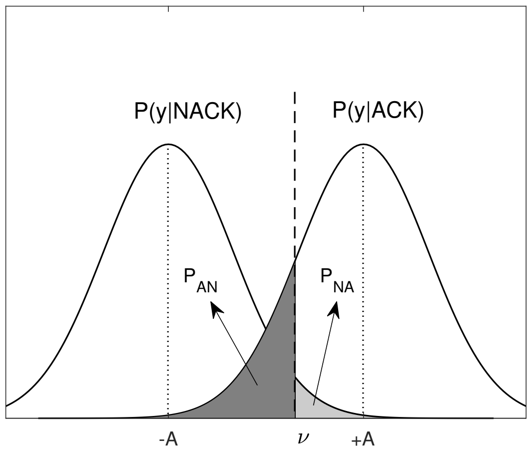

Fig. 2. An illustration of decoding ACK/NACK signals.

In case an ACK signal is decoded erroneously as a NACK, the BS performs an unnecessary data retransmission. This results in wasting radio resources for performing the data retransmission. However, in case a NACK is decoded erroneously as an ACK, the BS does not perform the necessary retransmission round. This sacrifices the reliability of message delivery. The URLLC needs to take into account these error probabilities in order to meet the overall reliability constraint with optimized resource utilization [14], [7].

III. Optimization problem

This section formulates the optimization problem for allocating radio resources to the data channel, considering the errors of both data and control channels. The main objective is to minimize the assigned radio resources over the data channel while meeting the latency and reliability constraints. The BS intends to deliver k bits of information to the UE. We consider the data delivery with the maximum of two transmission rounds. The initial transmission is performed using n_1 channel uses. The UE then tries to retrieve the message and sends ACK/NACK accordingly. The data transmission is finished if the BS detects an ACK. Otherwise, the BS performs the data retransmission using n_2 channel uses. The UE tries to retrieve the message using all the received information. In this communication scenario, the average channel uses for the data channel reads

$$\overline{N} = n_1 + n_2 \times \left\{E(n_1, k, \gamma)(1 - P_{\mathsf{NA}}) + (1 - E(n_1, k, \gamma))\, P_{\mathsf{AN}}\right\}, \quad (5)$$

where γ is the SNR for the data channel. The retransmission round is performed if 1) the UE cannot retrieve the message from the initial transmission and a NACK signal is detected correctly, or 2) the UE retrieves the message from the initial transmission while an ACK signal is detected erroneously as a NACK. The success probability of decoding the message can

IV. Simulation results

In this section, we compare the performances of the symmetric and asymmetric ACK/NACK detection schemes for URLLC. We consider a scenario that the BS intends to deliver 32 bytes to the UE, i.e., $k = 256$ bits. The SNR of the data channel is $\gamma = 0$ dB. The reliability target for the communication is associated with the BLER of 10^{-5} and 10^{-7}.

Fig. 3 illustrates the probabilities of wrong ACK/NACK detection, applying symmetric and asymmetric signal detection approaches. The symmetric signal detection is applied by setting $\nu = 0$ regardless of feedback channel quality. However, the optimal threshold for asymmetric signal detection is derived according to the optimization (7). The optimal threshold varies according to the communication reliability target and the feedback channel quality. It can be concluded that $\nu \approx 0$ for low and high values of γ_f, as $P_{\mathsf{AN}} \approx P_{\mathsf{NA}}$ in these regions. However, $\nu > 0$ for the moderate values of γ_f as $P_{\mathsf{AN}} > P_{\mathsf{NA}}$. This indicates that NACK signals are favoured to be detected more reliably compared to the ACK signals.

Fig. 4 shows the optimal BLER for the initial transmission round, i.e., $E(n_1, k, \gamma)$ for both the symmetric and asymmetric signal detection strategies. For the low SNR levels of the feedback channel, the BLER for the initial transmission round is almost the same as the tolerable BLER for the communication, i.e., ϵ, regardless of the employed detection scheme. This is due to the fact that the feedback channel is unreliable in this region and it not possible to rely on the retransmission round to correct the errors of data delivery (For symmetric detection, $P_{\mathsf{AN}} = P_{\mathsf{NA}} \approx 0.5$). Hence, the initial transmission round should be performed with high reliability. Note that even the asymmetric ACK/NACK does not help as providing a high reliability for NACK detection leads to $P_{\mathsf{AN}} \approx 1$. This means that although the NACK signal can be decoded with high reliability, the ACK signal is always

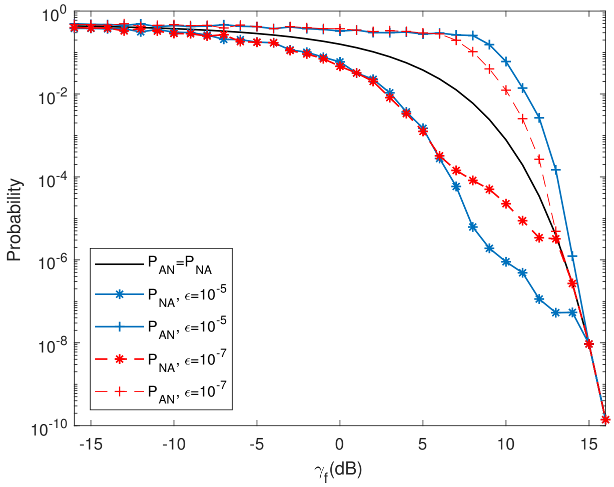

Fig. 3. Probabilities of missing ACK/NACK signals using symmetric and asymmetric signal detection for different reliability targets.

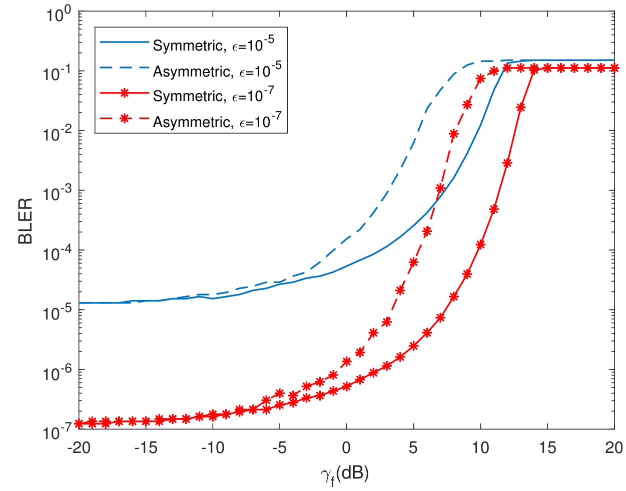

Fig. 4. Optimal BLER for the initial transmission round for symmetric and asymmetric signal detection for different reliability targets.

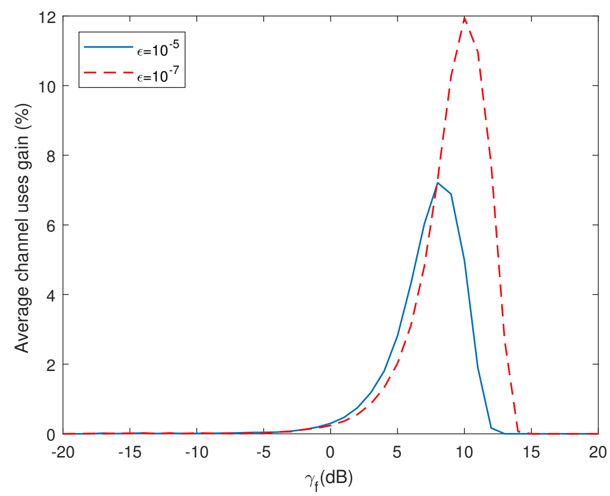

Fig. 5. Achieved gain by employing asymmetric ACK/NACK detection on the average channel uses for different reliability targets.

decoded erroneously as a NACK, which results in performing unnecessary retransmission. For the high SNR levels of the feedback channel ($\gamma_f > 13$ dB for $\epsilon = 10^{-5}$ and $\gamma_f > 15$ dB for $\epsilon = 10^{-7}$), the BLER for the initial transmission rounds is around 10%. The feedback channel is reliable enough in this region, hence, it is possible to perform the initial transmission round with a moderate BLER and rely on the retransmission round for correcting the errors of data delivery. The BLER of 10% is reported as an optimal target when the feedback channel is reliable enough [6], [7], [14]. For a moderate SNR levels of the feedback channel, the asymmetric detection provides a better protection for NACK signals. This allows relying more on the retransmission round for correcting the failure in delivering the data, consequently, allocating less channel uses to the initial transmission round, while utilizing more channel uses in the retransmission round.

Fig.5 depicts the gain of employing the asymmetric ACK/NACK detection on the average channel uses. The gain is calculated as $1-\overline{N}_{\text{Asymmetric}}/\overline{N}_{\text{Symmetric}}$. The figure reveals that for the moderate ranges of γ_f, the reduced channel uses in the initial transmission round has a higher impact on the average channel uses, compared to the increased number of channel uses in the retransmission round. Consequently, the average channel uses for the asymmetric ACK/NACK detection is less than one for the symmetric ACK/NACK detection. The achieved gain depends on the SNR for the feedback channel and the communication reliability target.

V. Conclusions

The reliability and latency constraints for URLLC entail considering the errors of data and control channels. This requires employing novel link adaptation schemes that take into account the qualities of both data and control channels. This paper investigates the effects of ACK/NACK detection on the communication efficiency of URLLC. Indeed, the communication efficiency is more sensitive to the reliability of NACK signal compared to the reliability of ACK signal. For this reason, the asymmetric signal detection is proposed to provide a better protection for the NACK signal. The simulation results reveal that the asymmetric signal detection can offer better resource utilization for the data channel.

Acknowledgment

This work was supported in part by the Finnish Funding Agency for Innovation (TEKES) under the project Wireless for Verticals (WIVE), which is a part of 5G Test Network Finland (5GTNF).

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