# NACK-Only HARQ Feedback via OOK Signaling and Energy Detection

Waddi Abdrahamane, Raymond Knopp, Sebastian Wagner
*Communication Systems Department*
*EURECOM*
Biot, France
waddi.abdrahamane@eurecom.fr, raymond.knopp@eurecom.fr, sebastian.wagner@eurecom.fr

***Abstract*—This paper investigates an On-Off Keying (OOK) signaling scheme for NACK-only HARQ feedback, motivated by the asymmetry of reliable downlink operation where ACK events occur with high probability. In the considered scheme, ACK is represented by silence and NACK by an energy-bearing signal, enabling sparse UE transmission. Assuming independent HARQ feedback bits with NACK probability $p$, we derive the false alarm and missed detection probabilities of the non-coherent energy detector and introduce the average UE transmission activity as a key metric. For $K$ HARQ bits, the OOK transmission activity is $1-(1-p)^K$, which can be significantly lower than always-on PUCCH feedback. Link-level simulations against NR PUCCH Formats 0 and 3 show that PUCCH achieves lower missed detection probability under equal resource and power normalization, while OOK reduces average UE activity by remaining silent for all-ACK feedback. The proposed framework characterizes a reliability-activity tradeoff relevant to NACK-only HARQ feedback mechanisms.**

***Index Terms*—HARQ, PUCCH, ACK, NACK, OOK, energy detection, non-coherent detection, false alarm, missed detection**

## I. Introduction

Hybrid automatic repeat request (HARQ) feedback is a fundamental component of reliable downlink transmission [1]. In 5G NR, HARQ-ACK information is typically reported through the physical uplink control channel (PUCCH), where the UE transmits feedback in each configured reporting occasion after downlink scheduling. However, in reliable downlink operation, HARQ feedback is often highly asymmetric: ACK events occur with high probability, whereas NACK events are relatively rare. This asymmetry motivates the study of sparse feedback mechanisms in which the UE remains silent for ACK and transmits only when a NACK occurs. NACK-only and UE-initiated HARQ-ACK feedback have recently been discussed in 3GPP as possible mechanisms for reducing uplink control signaling and UE transmit activity [2]. In particular, NACK-triggered feedback can reduce uplink resource usage when decoding failures are rare. Furthermore, NACK-only feedback may require modified receiver processing and can suffer a reliability loss compared with conventional PUCCH-based ACK/NACK signaling. Motivated by these observations, this paper investigates an on-off keying (OOK) physical-layer signaling approach for NACK-only HARQ feedback. In the proposed scheme, ACK is represented by silence, whereas NACK is represented by an energy-bearing signal. The receiver applies non-coherent energy detection and selects the detection threshold to control the false alarm probability. The objective of this work is not to replace NR PUCCH as a reliability-optimized HARQ feedback mechanism, nor to resolve the higher-layer ambiguity between all-ACK and Discontinuous Transmission (DTX) [2]. Instead, we quantify the physical-layer tradeoff between reduced UE transmission activity, false alarm probability, and missed detection probability. The contributions of this paper are summarized as follows:

- We formulate NACK-only HARQ feedback as a sparse OOK signaling problem, where ACK corresponds to silence and NACK corresponds to energy transmission.
- We derive the non-coherent OOK energy detector and characterize its false alarm and missed detection probabilities under asymmetric HARQ priors.
- We introduce the average UE transmission activity as a metric for NACK-only feedback and show that, for NACK probability $p$ and $K$ feedback bits, the OOK transmission probability is $1-(1-p)^K$, whereas conventional PUCCH feedback transmits in every feedback occasion.
- We compare the proposed OOK detector with NR PUCCH Formats 0 and 3, highlighting the tradeoff between reduced uplink activity and missed detection performance.

The remainder of the paper is organized as follows. Section II introduces the system model. Section III presents the single-bit OOK detector and its performance analysis. Section IV extends the analysis to $K > 1$ bits with prior-aware detectors. Section V presents simulation results and comparisons.

## II. System Model

We consider uplink HARQ feedback transmission from a UE to a gNB. The UE transmits a $K$-bit binary vector $\mathbf{b} = [b_0, \dots, b_{K-1}]^T, b_k \in \{0,1\}$, where $b_k = 0$ indicates ACK and $b_k = 1$ indicates NACK for the $k$-th HARQ process. Each bit is independently distributed with

$$\Pr(b_k = 1) = p, \quad \Pr(b_k = 0) = 1 - p, \tag{1}$$

where $p \approx 10\%$ in a typical 5G NR scenario [2], [3].

In the proposed OOK scheme, each HARQ bit is mapped to one OOK dimension. The $k$-th dimension is silent for ACK and active for NACK. The received baseband sample for the $k$-th bit is

$$H_0 : y_k = n_k \qquad (b_k = 0,\ \text{ACK}), \tag{2}$$
$$H_1 : y_k = Ae^{j\theta_k} + n_k \qquad (b_k = 1,\ \text{NACK}), \tag{3}$$

where $A > 0$ is the real signal amplitude, $\theta_k \sim \mathcal{U}[0, 2\pi)$ is an unknown channel phase, and $n_k \sim \mathcal{CN}(0, \sigma^2)$ is complex AWGN with variance $\sigma^2$. The signal energy is $A^2$.

## III. Single-Bit OOK Detection

We first consider the single-bit case to derive the basic non-coherent OOK energy detector and its false alarm and missed detection probabilities, which will subsequently be extended to the multiple feedback bits.

### *A. Neyman-Pearson (NP) Test*

For $K = 1$, the detection problem is a binary hypothesis test on the scalar observation $y = y_0$. Since the channel phase $\theta$ is unknown and uniformly distributed, we compute the marginal likelihood under $H_1$ by averaging over $\theta$:

$$p(y|H_1) = \frac{1}{\pi\sigma^2} \exp\left(-\frac{|y|^2 + A^2}{\sigma^2}\right) I_0\left(\frac{2A|y|}{\sigma^2}\right), \tag{4}$$

where $I_0(\cdot)$ is the modified Bessel function of the first kind of order zero. Under $H_0$ the likelihood is given by:

$$p(y|H_0) = \frac{1}{\pi\sigma^2} \exp\left(-\frac{|y|^2}{\sigma^2}\right). \tag{5}$$

Therefore, both hypotheses are fully specified, and the problem becomes a simple-versus-simple binary hypothesis test where we can use the NP lemma. The corresponding likelihood ratio is

$$\Lambda(y) = e^{-A^2/\sigma^2}\, I_0\left(\frac{2A|y|}{\sigma^2}\right). \tag{6}$$

Since $I_0(\cdot)$ is strictly increasing and monotonic in $|y|$, the NP test reduces to an *energy detector* with test statistic $T$ and threshold $\gamma$:

$$T = |y|^2 \underset{H_0}{\overset{H_1}{\gtrless}} \gamma. \tag{7}$$

By the Neyman–Pearson lemma, this detector is optimal for the scalar binary hypothesis test, i.e., it maximizes the probability of detection for a given false alarm probability [4].

### *B. False Alarm and Missed Detection Probabilities*

For the scalar OOK detector, we first define the conditional single bit false alarm and missed detection probabilities. Under $H_0$, the receiver observes $y = n \sim \mathcal{CN}(0, \sigma^2)$. Hence,

$$\frac{2T}{\sigma^2} = \frac{2|y|^2}{\sigma^2} \sim \chi_2^2,$$

and $T = |y|^2$ is exponentially distributed with mean $\sigma^2$. Therefore, the conditional false alarm probability is

$$\begin{aligned}\alpha &= \Pr(\hat{b} = 1|b = 0) = \Pr(T > \gamma|H_0)\\ &= \exp\left(-\frac{\gamma}{\sigma^2}\right).\end{aligned} \tag{8}$$

Thus, for a single bit target false alarm probability $\alpha$, the corresponding threshold is $\gamma = -\sigma^2 \ln(\alpha)$.

Under $H_1$, $T/(\sigma^2/2)$ follows a noncentral chi-squared distribution with two degrees of freedom and noncentrality parameter $2A^2/\sigma^2$. The conditional NACK detection probability is

$$\begin{aligned}\beta &= \Pr(\hat{b} = 1|b = 1) = \Pr(T > \gamma|H_1)\\ &= Q_1\left(\sqrt{\frac{2A^2}{\sigma^2}}, \sqrt{\frac{2\gamma}{\sigma^2}}\right),\end{aligned} \tag{9}$$

where $Q_1(\cdot,\cdot)$ is the first-order Marcum $Q$-function. The corresponding conditional missed detection probability is

$$\begin{aligned}\mu &= \Pr(\hat{b} = 0|b = 1) = 1 - \beta\\ &= 1 - Q_1\left(\sqrt{\frac{2A^2}{\sigma^2}}, \sqrt{\frac{2\gamma}{\sigma^2}}\right).\end{aligned} \tag{10}$$

The quantities $\alpha$, $\beta$, and $\mu$ are conditional single-bit probabilities. In the multi-bit case, the false alarm and missed detection metrics are defined as $K$-bit union-event probabilities, as described in the next section.

## IV. Multi-Bit OOK

### *A. Detector*

For $K > 1$, $\mathbf{b}$ and $\mathbf{y} = [y_0, \ldots, y_{K-1}]^T$ are the transmit and receive vectors, respectively. Assuming *independent* OOK dimensions, the joint likelihood factors as

$$p(\mathbf{y}|\mathbf{b}) = \prod_{k=0}^{K-1} p(y_k|b_k). \tag{11}$$

Therefore, the scalar energy detector derived in Section III can be applied independently to each OOK dimension:

$$\hat{b}_k = \begin{cases} 1, & T_k \geq \gamma,\\ 0, & T_k < \gamma. \end{cases} \tag{12}$$

This detector is obtained by applying the scalar Neyman–Pearson energy test per dimension. The resulting $K$-bit error metrics are union-event probabilities over the feedback bits.

### *B. False Alarm and Missed Detection Probabilities for $K > 1$*

For $K$ *independent* feedback bits, we define the false alarm $P_{\text{FA}}^{(K)}$ as the event that at least one ACK bit is detected as NACK:

$$P_{\text{FA}}^{(K)} = \Pr(\exists k : b_k = 0, \hat{b}_k = 1). \tag{13}$$

Similarly, the missed detection probablity $P_{\text{MD}}^{(K)}$ is the event that at least one NACK bit is detected as ACK:

$$P_{\text{MD}}^{(K)} = \Pr(\exists k : b_k = 1, \hat{b}_k = 0). \tag{14}$$

These are prior-weighted union-event probabilities under the HARQ feedback prior, where each bit is NACK with probability $p$, and should be distinguished from the conditional single-bit quantities $\alpha$, $\beta$, and $\mu = 1 - \beta$. Let $\alpha = \Pr(\hat{b}_k = 1|b_k = 0)$

and $\beta = \Pr(\hat{b}_k = 1 | b_k = 1)$. Then $1-\beta$ is the conditional single-bit missed detection probability.

For $K = 2$, the UE transmits $(b_0, b_1) \in \{(0,0),(0,1),(1,0),(1,1)\}$. By independence across OOK dimensions, the false alarm probability is

$$P_{\mathrm{FA}}^{(2)} = (1-p)^2\big[1-(1-\alpha)^2\big] + 2p(1-p)\alpha, \tag{15}$$

and the missed detection probability is

$$P_{\mathrm{MD}}^{(2)} = 2p(1-p)(1-\beta) + p^2(1-\beta^2). \tag{16}$$

These expressions show the combinatorial structure of the $K$-bit union events. Terms weighted by $p^j(1-p)^{K-j}$ correspond to feedback words with exactly $j$ NACK bits. For a transmitted feedback word containing exactly $j$ NACK bits, the prior probability is $\binom{K}{j}p^j(1-p)^{K-j}$. For this word, there are $K-j$ ACK bits. The conditional probability that at least one of these ACK bits is detected as NACK is $1-(1-\alpha)^{K-j}$. Therefore,

$$\begin{aligned} P_{\mathrm{FA}}^{(K)} &= \sum_{j=0}^{K}\binom{K}{j}p^j(1-p)^{K-j}\Big[1-(1-\alpha)^{K-j}\Big] \\ &= 1-\big(1-(1-p)\alpha\big)^K. \end{aligned} \tag{17}$$

Similarly, for a word containing $j$ NACK bits, the conditional probability that at least one NACK bit is missed is $1-\beta^j$. Thus,

$$\begin{aligned} P_{\mathrm{MD}}^{(K)} &= \sum_{j=1}^{K}\binom{K}{j}p^j(1-p)^{K-j}\big(1-\beta^j\big) \\ &= 1-\big(1-p+p\beta\big)^K. \end{aligned} \tag{18}$$

Equations (17) and (18) are consistent with the explicit expressions for $K = 2$.

The analytical multi-bit expressions in this section assume a fixed per-active-dimension OOK amplitude $A$. Therefore, each transmitted NACK dimension has the same energy, independently of the number of NACKs in the feedback word. Under this model, the total active feedback energy increases with the number of NACKs. In the link-level simulations an additional power normalization is applied so that the available OOK transmit energy is shared among the active NACK dimensions. Consequently, the analytical expressions should be interpreted as a baseline reference rather than an exact prediction of the power-normalized link-level curves.

## V. Simulation Results

All schemes are evaluated at $p = 0.1$, corresponding to a 10% NACK probability, over the SNR range $[-10, 15]$ dB. The OOK threshold is selected to satisfy the reference $K$-bit false alarm constraint $P_{\mathrm{FA}}^{(K)} = 1\%$ [6]. We compare the proposed OOK-based NACK-only feedback with NR PUCCH Formats 0 and 3 for small HARQ-ACK payloads [7] in a GPU-accelerated Sionna/PyTorch-based simulator.

The link-level simulation parameters are summarized in Table I. PUCCH Format 0 and PUCCH Format 3 use $L = 3$ and $L = 4$ OFDM symbols, respectively.

| Parameter | Value |
|---|---|
| Carrier Frequency / Sub-carrier spacing | 2.6 GHz / 30 kHz |
| System Bandwidth | 20 MHz (51 PRBs) |
| Transmit antennas $N_{\mathrm{tx}}$ | 1 |
| Receive antennas $N_{\mathrm{rx}}$ | 2 |
| HARQ payload size | $K \in \{1,2,3\}$ |
| Transmission Bandwidth | 1 PRB |
| Channel | AWGN, TDL-C 300ns |
| UE Speed | 0-3 km/h |

TABLE I: Link-level simulation parameters.

For the OOK waveform, the $K$ HARQ feedback bits are mapped to $K$ contiguous sub-carriers within one PRB and are repeated over the allocated OFDM symbols when more than one symbol is used. Therefore, OOK and the PUCCH references use the same 1 PRB allocation. For each configuration, we report two metrics, (i) the false alarm probability, and (ii) the missed detection probability.

The OOK waveform is power-normalized within the allocated resource. When $d$ NACK bits are active, the available OOK energy is divided equally among the $d$ active dimensions. For a NACK probability $p$, the probability of a nonzero OOK transmission is

$$P_{\mathrm{tx}}^{\mathrm{OOK}} = \Pr(\text{at least one NACK}) = 1-(1-p)^K.$$

By contrast, conventional PUCCH Format 0 transmits a feedback signal in every feedback occasion, so $P_{\mathrm{tx}}^{\mathrm{PF0}} = 1$. Hence, the normalized average UE transmission activity of OOK relative to PUCCH Format 0 is

$$\frac{P_{\mathrm{tx}}^{\mathrm{OOK}}}{P_{\mathrm{tx}}^{\mathrm{PF0}}} = 1-(1-p)^K. \tag{19}$$

For $p = 0.1$, this gives $P_{\mathrm{tx}}^{\mathrm{OOK}} = 0.1$ for $K = 1$, $P_{\mathrm{tx}}^{\mathrm{OOK}} = 0.19$ for $K = 2$ and $P_{\mathrm{tx}}^{\mathrm{OOK}} = 0.271$. Thus, the UE remains silent approximately 90%, 81% and 72.9% of the feedback occasions for $K = 1$, $K = 2$ and $K = 3$, respectively.

For the link-level implementation, the OOK detector is applied to an averaged energy statistic over the allocated OFDM symbols $L$ and receive antennas. Let $N_{\mathrm{avg}} = LN_{\mathrm{rx}}$. For the $k$-th OOK dimension, the statistic is

$$T_k = \frac{1}{N_{\mathrm{avg}}}\sum_{m=1}^{N_{\mathrm{avg}}}|y_{k,m}|^2. \tag{20}$$

Under the ACK hypothesis, no OOK signal is transmitted on that dimension, and

$$\frac{2N_{\mathrm{avg}}T_k}{N_0} \sim \chi^2_{2N_{\mathrm{avg}}}. \tag{21}$$

Therefore, the threshold is computed as

$$\gamma = \frac{N_0}{2N_{\mathrm{avg}}}\chi^{-2}_{2N_{\mathrm{avg}},\mathrm{isf}}(\alpha), \tag{22}$$

where $\chi^{-2}_{2N_{\mathrm{avg}},\mathrm{isf}}(\cdot)$ denotes the inverse survival function of a central chi-square random variable with $2N_{\mathrm{avg}}$ degrees of freedom. Given $P_{\text{FA}}^{(K)}$ and $p$, the corresponding per-inactive-bit false alarm probability is

$$\alpha = \frac{1 - \left(1 - P_{\text{FA}}^{(K)}\right)^{1/K}}{1 - p}. \tag{23}$$

The PUCCH receiver use non-coherent PUCCH MAP detectors [5], which select the message $m$ such that $\hat{m}_{\text{MAP}} = \arg\max_m p(\mathbf{y}|m)P(m)$ with $P(m)$ function of the ACK/NACK priors.

Figures 1, 2 and 3 show the performance in AWGN for $K = 1, 2$ and 3, respectively. The false alarm probability for PF0 is bell-shaped because the MAP decision is prior-dominated at low SNR, likelihood-dominated at high SNR, and influenced by both terms at intermediate SNR. For $p = 0.1$, the detector is biased towards ACK decisions, which suppresses false alarms. At intermediate SNR, noise fluctuations can overcome this ACK-prior advantage and produce NACK-containing decisions, increasing $P_{\text{FA}}^{(K)}$. At high SNR, the correct dimension dominates and both error probabilities decrease. The OOK $P_{\text{FA}}^{(K)}$ is at $10\%$ as we fixed it to derive the threshold. The PUCCH $P_{\text{MD}}^{(K)}$ remain lower than that of OOK under equal resource and power normalization, as shown in Figs. 1–5. Applying an OOK power boost under the same peak-power constraint reduces this missed detection gap.

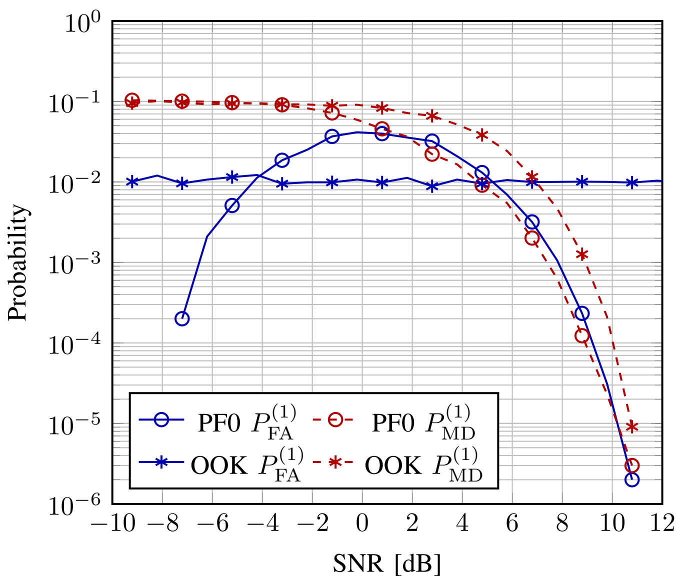


Fig. 1: $K = 1$ and one OFDM symbol: OOK vs. PUCCH Format 0 over non-coherent AWGN.

Table II summarizes the measured time-domain peak power, average power, and Peak-to-Average Power Ratio (PAPR). For OOK, the PAPR is computed over active NACK-containing transmissions. Under an equal peak-power constraint, OOK can therefore be uniformly boosted by $13.55$ dB in the one-bit case relative to PUCCH Format 0 and by $1.48$ dB in the three-bit case relative to DFT-precoded PUCCH Format 3 with $\pi/2$-BPSK. This represents a peak-power margin rather than

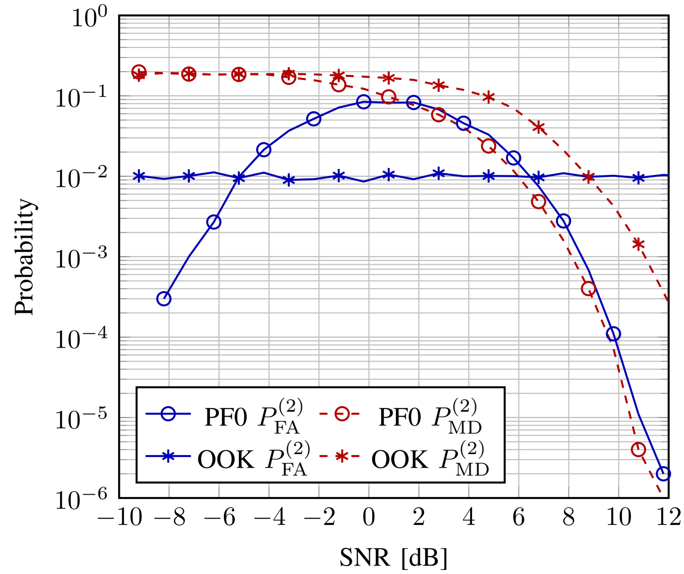


Fig. 2: $K = 2$ and one OFDM symbol: OOK vs. PUCCH Format 0 over non-coherent AWGN.

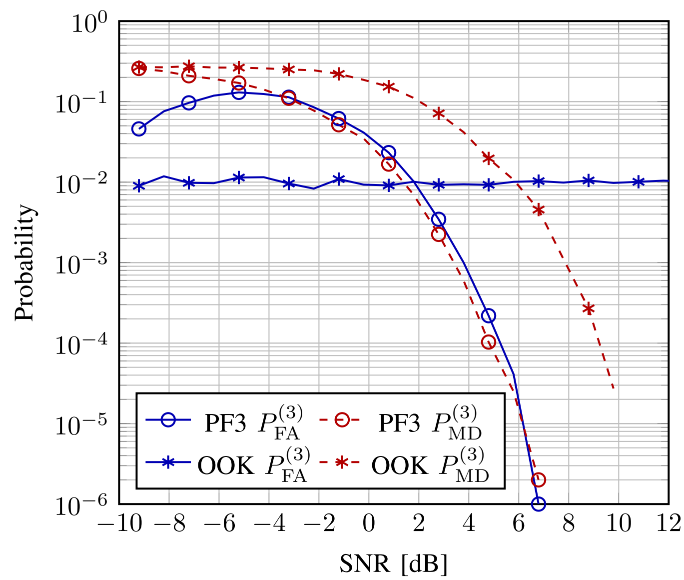


Fig. 3: $K = 3$ and four OFDM symbols: OOK vs. PUCCH Format 3 over non-coherent AWGN.

a PAPR advantage, since uniform boosting does not change the PAPR.

Figures 4 and 5 show the performance in TDL-C fading channels for $K = 1$ and $K = 2$, respectively. For $K = 1$, the false alarm behavior observed under non-coherent AWGN is approximately the same, whereas the multi-bit case exhibits a higher false alarm probability at large SNR. This indicates that the fixed non-coherent AWGN-calibrated threshold no longer fully controls the post-demodulation OOK energy statistic in frequency-selective fading. The OOK receiver statistic seems affected by channel-dependent scaling, so the noise-only en-

| Scheme | $K$ | $P_{\max}$ | $P_{\text{avg}}$ | PAPR |
|---|---|---|---|---|
| PF0 | 1,2 | $-10.53$ dB | $-13.30$ dB | 2.77 dB |
| OOK | 1 | $-24.08$ dB | $-24.08$ dB | 0.00 dB |
| OOK | 2 | $-15.20$ dB | $-20.64$ dB | 5.44 dB |
| PF3 $\pi/2$-BPSK DFT | 3 | $-09.61$ dB | $-13.44$ dB | 3.83 dB |
| OOK | 3 | $-11.09$ dB | $-18.75$ dB | 7.67 dB |

TABLE II: Measured peak power, average power, and PAPR.

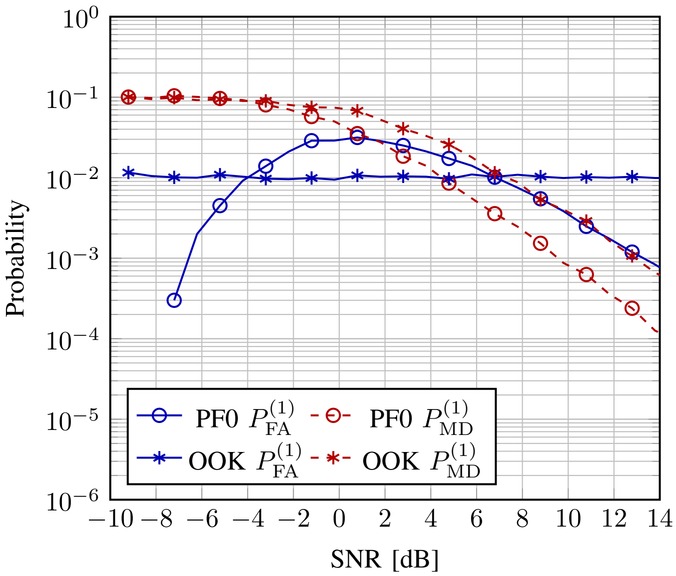


Fig. 4: $K = 1$ and one OFDM symbol: OOK vs. PUCCH Format 0 over a TDL-C fading channel.

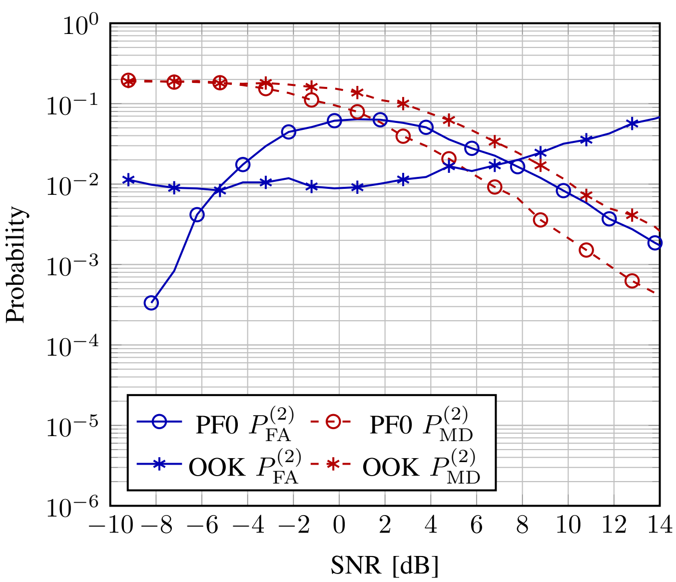


Fig. 5: $K = 2$ and one OFDM symbol: OOK vs. PUCCH Format 0 over a TDL-C fading channel.

ergy distribution differs from the scalar non-coherent AWGN model. The fading-channel OOK receiver therefore requires channel- and noise-aware threshold calibration.

These results show that OOK should be interpreted as a low-activity physical-layer NACK indication rather than a direct replacement for reliability-optimized PUCCH feedback. Under equal resource and power normalization, NR PUCCH Formats 0 and 3 provide lower missed-detection probability for the considered small UCI payloads. However, under a clipping-limited peak-power constraint, OOK can be power-boosted due to its lower measured peak power relative to the considered PUCCH references. System-level issues such as the ambiguity between all-ACK silence, DTX, missed Downlink Control Information (DCI), and missed feedback occasions [8], [9] remain outside the scope of this physical-layer study and require protocol-level resolution. These related limitations of NACK-only feedback have been identified in industry discussions [2].

## VI. Conclusion

This paper investigated OOK signaling for NACK-only HARQ feedback, where ACK is represented by silence and NACK by an energy-bearing signal. We derived the false alarm and missed detection probabilities of the non-coherent OOK energy detector under asymmetric HARQ priors and introduced the average UE transmission activity. The results show that OOK can control the false alarm probability through threshold selection and significantly reduce UE transmit activity. For $p = 0.1$, the UE transmits in only 10%, 19%, and 27.1% of feedback occasions for $K = 1$, 2, and 3, respectively. This highlights the relevance of unequal HARQ priors for future feedback designs. However, the missed-detection performance loss relative to NR PUCCH and the protocol-level ambiguities associated with ACK silence limit the direct adoption of NACK-only feedback without additional system-level mechanisms.

## References


[1] 3GPP TS 38.213, "NR; Physical layer procedures for control", version 18.6.0 Release 18, 2025.

[2] R1-2601543, "FL summary for AI 10.5.4.3: 6GR HARQ related aspects," 3GPP TSG RAN WG1 Meeting #124,Gothenburg, Sweden, document R1-2601543, Feb. 2026.

[3] A. Doshi, P. Sen, K. Ivanov, W. Yang, J. Namgoong, T. Yoo, J. Jiang, and T. Ji, "AI/ML-based encoder and decoder design for PUCCH HARQ-ACK payload," in *Proc. 13th Int. Symp. Topics Coding (ISTC)*, 2025, pp. 1–5, doi: 10.1109/ISTC65386.2025.11154632.

[4] S. M. Kay, *Fundamentals of Statistical Signal Processing, Volume II: Detection Theory*. Prentice Hall, 1998.

[5] J. G. Proakis and M. Salehi, *Digital Communications*, 5th ed. McGraw-Hill, 2008.

[6] 3GPP TS 38.104, "Base Station (BS) radio transmission and reception ", version 18.5.0 Release 18, 2024.

[7] 3GPP TS 38.211,"NR; Physical channels and modulation", version 18.6.0 Release 18, 2025.

[8] Qualcomm Incorporated, "HARQ related aspects," 3GPP TSG RAN WG1 Meeting #125, Dalian, China, document R1-2604704, May 18–22, 2026.

[9] China Telecom, "Discussion on HARQ-related aspects," 3GPP TSG RAN WG1 Meeting #125, Dalian, China, document R1-2604302, May 18–22, 2026.