Analysis of Feedback Error in Automatic Repeat reQuest

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Abstract

The future wireless networks envision ultra-reliable communication with efficient use of the limited wireless channel resources. Closed-loop repetition protocols where retransmission of a packet is enabled using a feedback channel has been adopted since early days of wireless telecommunication. Protocols such as automatic repeat request (ARQ) are used in today’s wireless technologies as a mean to provide the link with reduced rate of packet outage and increased average throughput. The performance of such protocols is strongly dependent to the feedback channel reliability. This paper studies the problem of feedback error and proposes a new method of acknowledging packet delivery for retransmission protocols in unreliable feedback channel conditions. The proposed method is based on backwards composite acknowledgment from multiple packets in a retransmission protocol and provides the scheduler of the wireless channel with additional parameters to configure ultra-reliable communication for a user depending on channel quality. Numerical analysis are presented which show orders of magnitude increase in reliability of the proposed method as compared to ARQ at the cost of a small increase in average experienced delay.

I. INTRODUCTION

Repetition of a packet over non-deterministic channel conditions is a prominent approach to reliable packet delivery. Wireless telecommunications technologies such as high speed packet access (HSPA), worldwide interoperability for microwave access (WiMax) and long term evolution (LTE), to mention a few, have relied on the performance boost provided by retransmission techniques such as ARQ and hybrid automatic repeat request (HARQ) [1]. Such retransmission protocols add to the robustness of transmission and increase link throughput. In LTE, and as expected for the 5th generation mobile networks (5G) [2], ARQ is used in the radio link control (RLC) layer while HARQ in the lower Media Access Control (MAC) and upper physical layer (PHY) layer. Performing together, these retransmission protocols provide the system with high
reliability where failure in the MAC layer HARQ operation is compensated for by the RLC layer ARQ in acknowledged mode at the expense of extra experienced latency for the packet [3].

The role of feedback channel is to limit repetitions to only when the initial attempt is failed thus, increasing data channel efficiency. However, inevitable feedback channel impairments may cause unreliability in packet delivery. A decoding failure report, i.e. negative acknowledgement (NAK), falsely received as positive acknowledgement (ACK) results in undesirable packet outage. Attempts to increase feedback reliability, e.g., by means of repetition coding, is costful to the receiver node while erroneous feedback detection may cause an increased packet delivery latency and diminish throughput and reliability key performance indicators (KPIs). E.g., in LTE a single-bit ACK/NAK spans over multiple resource element (RE) up to a physical resource block (PRB) in up-link (UL) and down-link (DL) HARQ respectively to reduce false feedback detection [4], making feedback bits too costly to the network. In newer releases of LTE, blind HARQ retransmissions of a packet is considered as a solution to avoid feedback complexity of broadcast HARQ and increase reliability [5]. Such approach, despite the offered simplicity, can severely decrease resource utilization efficiency of the system considering that typically a high percentage of transmissions are successfully decoded in the initial attempt in typical link adaptation configurations.

The core question this paper tries to answer is how to reliably design a feedback-based retransmission protocol in unreliable feedback conditions. We first study the effect of erroneous feedback on performance of retransmission protocols. We assume a simple stop-and-wait (SAW) mode of operation in a narrow-band wireless link where the receiver node is a low-cost and low-energy device with limited power for feedback channel acknowledgement reports. Such model portrays well the unreliable feedback channel problem where the straight-forward solution to acquire reliable packet delivery is by either adding diversity gain to the feedback link or relaxing the dependency to feedback channel and performing blind or conservative retransmission of the packet. Specifically, for low-cost narrow-band communication such diversity gain can be achieved by increasing time diversity order of the feedback channel. We study different approaches of increasing feedback channel time diversity and establish achievable reliability regions with respect to feedback channel error rate. We show that in reasonably reliable feedback channel conditions where the product of packet error rate and feedback error rate is comparable to packet outage rate, conservative asymmetric feedback detection can provide the required
reliability level by slightly increasing false NAK rate while reducing false ACK rate. Further, in extremely un-reliable feedback channel conditions we see that blind retransmission of packet is the viable solution in terms of reliability while it zeros the receiver node’s energy consumption over feedback channel.

Next, we propose a new method of backwards composite acknowledgment that helps improves reliability of repetition process without the need to increase time diversity order of the feedback channel. The proposed scheme relies on collaboration between transmitter and receiver nodes to provide ultra-reliable communication of packets even in poor feedback channel conditions. Furthermore, thanks to the additional design parameters provided by the proposed method, the scheduler of wireless network is able to configure each communication node with desirable ultra-reliability only using one layer of retransmission protocol. This enables the wireless technologies such as LTE to adopt one layer of retransmission protocol with configurable reliability level as opposed to stacked two-layer ARQ/HARQ operation that is currently deployed.

The rest of this paper is organized as follows: in Sec. II the unreliability problem of retransmission protocols caused by feedback channel unreliability feedback error problem is studied; Sec. III introduces the backwards composite feedback solution for reliable packet delivery; in Sec. IV numerical results are presented to evaluate the performance of the proposed solution; finally, Sec. V covers the concluding remarks.

II. PROBLEM DESCRIPTION

In this study we adopt the SAW mode of operation for retransmission protocols which works as follows. First, at time $i$ the $j$th packet arrived from a higher layer application denoted by $P^j_i$ is transmitted by transmitter node for the first time. Next, receiver node attempts decoding on the observed packet denoted by $\tilde{P}^j_i$. Using a feedback channel, receiver node sends the decoding success report $A_i$ at corresponding feedback instance $i$, where $A_i = 1$ in case of ACK and $A_i = 0$ in case of NAK (respectively, decoding success and decoding failure). Feedback transmission, similar to the data transmission, is assumed to be subject to channel impairments. We use $\tilde{A}_i$ to denote the feedback observed by the transmitter node at feedback time instance $i$. In case of observing a NAK the same data packet $\tilde{P}^j_i$ is retransmitted at the next transmit time instance $i + 1$.

\footnote{In practice the same message can be conveyed in different set of coded bits called \textit{redundancy versions}.}
(i.e., \( P_{i+1}^j \)), otherwise, transmission of a new data packet is initiated (i.e., \( P_{i+1}^{j+1} \)). Retransmission of a NAKed packet continues until ACK is observed over the feedback channel or maximum \( M \) transmission attempts for the packet is reached. Therefore, at transmitter node a packet is only regarded as delivered if ACK is observed and otherwise it is regarded as failed. The transmitter node sends a single-bit new data indicator (NDI) message per transmit data packet \( P \). The single-bit NDI is toggled every time a packet is transmitted for the first time. We assume that receiver is able to detect NDI error-free. The duration between transmit occasions \( i \) and \( i+1 \) is denoted by round trip time (RTT) where only one packet transmit occasion and one feedback occasion are considered in each RTT.

Reliability of packet delivery in SAW operation with feedback channel is limited by both packet transmission block error probability (BLEP) and feedback detection error rate. We use \( p_e = p_e^1 \) and \( p_e^m \) for integer \( m \) to denote BLEP of a packet after one and \( m \) transmission attempts respectively where, by definition \( p_e^0 = 1 \). We assume independent and identically distributed (i.i.d.) block fading channel model for packet transmission. Therefore, we have \( p_e^m \leq (p_e)^m \) where equality holds only if the decoder utilizes no combining gain (e.g., in case of ARQ operation). Feedback channel is assumed to follow the binary asymmetric channel (BAC) model where error probability varies depending on the input symbol to the channel. Error probabilities for such channel model are described as follows.

\[
p_0 = \Pr \{ \tilde{A}_i = 1 | A_i = 0 \} \\
p_1 = \Pr \{ \tilde{A}_i = 0 | A_i = 1 \}
\]

We assume that instances of the feedback channel are independent from each other and from data channel. Such model for the feedback channel is simplified as compared to real-life feedback channel where an extra message (e.g., discontinued transmission (DTX)) may also be considered as input to the feedback channel. E.g., in case of LTE technology, DTX may indicate failure in detection of the scheduling grant for data transmission \[3\]. Throughout this paper we reserve the notation \( \bar{a} \) to denote \( \bar{a} = 1 - a \) for any real valued \( a \) where \( a \in [0, 1] \).

In a retransmission protocol where retransmissions are triggered by NAK feedback, in case of NAK→ACK error the transmitter node will mistakenly drop the packet assuming it is successfully decoded at the receiver. Therefore, it is crucial to reduce the effective chances of a packet
being discarded as a result of false ACK. The straightforward solution to reduce chances of NAK→ACK is to increase reliability of the feedback channel (i.e., reducing $p_0$) e.g., by increasing repetition order of feedback transmission by factor of $L > 1$. However, such solution stretches feedback message in time, frequency or power domains, requiring extra resources. Specifically, in scenarios where receiver node has limited power and bandwidth for feedback transmission (e.g., narrow-band and low-cost massive machine type of communication (mMTC) receivers) the cost of increasing feedback reliability is additional time diversity for feedback which in turn increases the experienced delay and receiver node power consumption. We use $T$ to denote the number of feedback occasions utilized for a packet before it is dropped at the transmitter (either considered delivered or failed). The average number of feedback occasions utilized per packet is then denoted by $T = \mathbb{E}\{T\}$ which, in time diversity scenario for feedback, is equivalent to the average delay experienced by the higher-layer application per packet. Further, we denote the events of decoding failure and success for $P^j_i$ in maximum $m$ transmission attempts by $F^{m}_j$ and $S^{m}_j$ respectively. Outage probability, $P_{\text{out}}$, is defined as the probability of decoding failure after maximum $M$ attempts, i.e., $P_{\text{out}} = \Pr\{F^{M}_j\}$. Data channel utilization is measured by the average number of transmission attempts per packet and is denoted by $\bar{N}$. We use $\tau$ to denote the packet delivery latency defined as the time duration it takes from the first transmission attempt of a packet until it is correctly decoded at the receiver. Assuming zero processing time at the receiver node we have $\tau = \text{TTI} + k \times \text{RTT}$ where $k > 0$.

In the following we first study the effects of feedback error on $P_{\text{out}}$ performance of retransmission protocols. Later in the next section we proposes a new feedback reporting scheme that suits low-cost and low-energy narrow-band wireless devices in ultra-reliable packet delivery. We start by investigating different feedback reporting approaches and analyze the trade-off between reliability and feedback time diversity order $L$.

1) Regular SAW (Reg-SAW): We assume the binary symmetric channel (BSC) model with $p_0 = p_1 = p$ for feedback channel. As shown in Fig. 1, in a SAW process, packet $P^j_i$ is initially transmitted over $i$th (blue color) transmit occasion which has duration of a transmission time interval (TTI). The numbers inside the transmit occasion blocks indicates data packet index $j$ from $P^j_i$ where $j$ is a positive integer. Followed by transmission of the packet, after a given propagation and receiver processing time [6], acknowledgement for the packet arrives. Next, transmitter node transmits the next packet $P^{j+1}_{i+1}$ in case of ACK (green color blocks) or retransmits
a version of the same packet $P^j_{i+1}$ (grey color blocks) in case of NAK (red color blocks). NDI is transmitted with each packet transmit occasion to notify the receiver of whether a new packet is transmitted (toggled NDI) or the same packet is retransmitted (un-toggled NDI). In principle ACK observance can be result of either a successful packet decoding followed by correct feedback detection or decoding failure followed by false feedback. In order to make it simple to follow the illustrations the packet index corresponding to each feedback occasion is shown inside the feedback occasion blocks.

The duration between transmit occasions $i$ and $i + 1$ is denoted by RTT. Without loss of generality, the propagation and processing time duration will be skipped in the illustrations after Fig. 1. Therefore, acknowledgement of each packet will be shown below it while the next transmit occasion starts immediately after.

![Figure 1: Stop-and-wait operation.](image)

2) *Increased feedback repetition order (L-Rep-ACK):* To increase feedback reliability for a receiver node with narrow-band low-energy feedback transmission a simple solutions is to increase time diversity of feedback transmission by $L > 1$. In this model each feedback transmission is stretched over $L$ feedback occasions where packet is declared as *delivered* at the transmitter node only if all $L$ observances of feedback are ACK. Otherwise, the packet is retransmitted by the $L$-Rep-ACK process. Therefore, probability of false ACK reduces to $P^L_0$ compared to that of $P_0$ in case of Reg-SAW. Further, due to feedback repetition, RTT of $L$-Rep-ACK is $L$ times that of Reg-SAW. NDI is used in similar way as in Reg-SAW to notify receiver node about retransmissions.

3) *L required ACK per packet (L-ACK-SAW):* In this approach, the acknowledgment generated for a packet is repeated over feedback occasions by the receiver node until $L > 1$ number of ACK observances are made at the transmitter node which in turn will trigger initiating the transmission of a new packet. A retransmission of the same packet is followed immediately if
Figure 2: $L$-Rep-ACK operation for $L = 3$.

NAK is observed while using NDI receiver is notified about the retransmission. Note that in this approach transmitter node keeps counting the number of ACK observances for a packet and $L$ required ACK observances may be received in non-consecutive occasions unlike $L$-Rep-ACK approach where $L$ observances of ACK must be counted consecutively.

Figure 3: $L$-ACK-SAW operation for $L = 3$.

4) Retransmission until $L$ ACKs are observed (ReTx-$L$-ACK): In this approach, similar to $L$-ACK-SAW, transmitter node requires $L$ observance of ACK before considering a packet as delivered. However, transmitter continues retransmission of the packet while observing the feedback channel. Therefore, ReTx-$L$-ACK transmits each packet at least $L$ times and stops retransmission when $L$ times ACK observances are made or maximum $M$ transmission attempts is reached. Fig. 4 depicts ReTx-$L$-ACK process for $L = 3$ where retransmission of packet $P_1$ is continued until 3 non-consecutive ACKs are detected.

Figure 4: ReTx-$L$-ACK operation for $L = 3$.

5) Asymmetric feedback detection for SAW (Asym-SAW): A different approach to decrease the false ACK rate is by using asymmetric detection of the binary feedback channel. For instance, let’s assume an additive white Gaussian noise (AWGN) feedback channel and a binary phase shift
keying (BPSK) symbol that conveys the single-bit feedback acknowledgement, where the binary 0 and 1 inputs of the feedback channel are represented in the signal constellation for BPSK in terms of energy per bit $E_b$ respectively by $-\sqrt{E_b}$ and $\sqrt{E_b}$. Assuming coherent detection and perfect recovery of the carrier frequency and phase, from signal modulation and detection theory we know that the bit error probability (BEP) with symmetric decision regions [7] is as follows,

$$p = \frac{1}{2} \text{erfc} \left( \sqrt{\frac{E_b}{N_0}} \right),$$

(3)

where $p$ denotes detection error probability, $N_0$ denotes the additive noise power spectral density and the complementary error function $\text{erfc} \left( \cdot \right)$ is defined as, $\text{erfc} \left( x \right) = \frac{2}{\pi} \int_x^\infty \exp(-t^2) \, dt$. Asymmetric decision regions, e.g., by moving the detection threshold in the BPSK constellation from origin to the point $\alpha \times \sqrt{E_b}$ (closer to $\sqrt{E_b}$ than $-\sqrt{E_b}$ for $\alpha > 0$), decreases the modified chances of false ACK detection $q_0$, while the modified false NAK rate $q_1$ increases accordingly. This reduces the chances of discarding unsuccessful packets at the transmitter while in turn increases chances of unnecessary retransmissions. The modified error probabilities for such asymmetric detection is then as follows.

$$q_0 = \frac{1}{2} \text{erfc} \left( (1 + \alpha) \sqrt{\frac{E_b}{N_0}} \right)$$

(4)

$$q_1 = \frac{1}{2} \text{erfc} \left( (1 - \alpha) \sqrt{\frac{E_b}{N_0}} \right)$$

(5)

Asym-SAW follows similar algorithm as in Reg-SAW where NDI signal is utilized to notify receiver node of retransmissions. For performance evaluation of this approach we assume BPSK modulation is used for the feedback channel where $E_b$ is chosen based on a given $p$ in (3). Then, the detection threshold is adjusted using parameter $\alpha$ in (4) and (5) to provide the required $q_0$.

6) **Blind retransmission (Blind-ReTx):** We further investigate the performance of blind retransmission without feedback. In such approach each packet is transmitted $M$ times by the transmitter node without requiring a feedback message from the receiver node.

Closed-form formulation for $P_{out}$, $\bar{N}$, $\bar{T}$ and cumulative density function (cdf) of packet delivery latency are shown in Table I, Table II, Table III and Table IV respectively for the approaches described in this section.

For an infinite allowed number of transmission attempts ($M \rightarrow \infty$) and assuming zero combining gain at the receiver (i.e., $p_e^m = (p_e)^m$), in Fig. 5 the outage probability $P_{out}$ of
Table I: Outage probability, $P_{\text{out}}$ for different feedback approaches.

| Feedback Approach | finite $M$                                                                 | $M \rightarrow \infty$                                                                 |
|-------------------|----------------------------------------------------------------------------|--------------------------------------------------------------------------------------|
| Reg-SAW           | $\sum_{m=1}^{M-1} p_e^m p_0 q_0^{m-1} + p_e^M q_0^{M-1}$                  | $\leq p_e p_0 \frac{1}{1-p_e q_0}$                                                   |
| $L$-Rep-ACK       | $\sum_{m=1}^{M-1} p_e^m p_0^L (1-p_0^L)^{m-1} + p_e^M (1-p_0^L)^{M-1}$     | $\leq p_e p_0^L \frac{1}{1-p_e (1-p_0^L)}$                                          |
| $L$-ACK-SAW       | $\sum_{m=1}^{M-1} p_e^m p_0^L q_0^{m-1} \left(\frac{L+m-2}{m-1}\right) +$ | $\approx p_e p_0^L \left(1 + \frac{p_e q_0}{(L-1)!(1-p_e q_0)^L}\right)$          |
| ReTx-$L$-ACK      | $\sum_{m=L}^{M-1} p_e^m p_0^L q_0^{m-1} \left(\frac{M-1}{L-1}\right)$      | $\approx p_e p_0^L \left(1 + \frac{p_e q_0}{(L-1)!(1-p_e q_0)^L}\right)$          |
| Asym-SAW          | $\sum_{m=1}^{M-1} p_e^m q_0^m q_0^{m-1} + p_e^M q_0^{M-1}$                 | $\leq p_e q_0 \frac{1}{1-p_e q_0}$                                                   |
| Blind Retx        | $p_e^M$                                                                   | $\rightarrow 0$                                                                     |

the above-listed feedback approaches is illustrated. Reliability of Reg-SAW is proportional to feedback reliability metric $p$ even in unbounded $M$ scenario. Specifically, the operation regions on Fig. 5 that are labeled by $R1, ..., R6$ for $P_{\text{out}}$ below $10^{-4}$ and $10^{-5}$ are not achievable using Reg-SAW. Therefore, for ultra-reliable communication it is required to either increase feedback diversity order $L$ or to perform blind retransmission without reliance on unreliable feedback channel. By increasing feedback time diversity order by $L = 2$, reliability regions $R1$ and $R4$ are achievable with proper choice of $M$. However, achieving regions $R2$ and $R5$ requires $L > 2$. Interestingly, Blind-ReTx with $M = 5$ and $6$ can achieve reliability in regions $R2$ and $R5$ respectively by refusing the dependency on feedback channel. However, as we see later in this paper such approach can be harmfully inefficient in resource utilization. Nevertheless, for highly unreliable feedback channel conditions such as in region $R6$, very large feedback diversity order $L \gg 4$ can have reverse effect on the performance efficiency parameters such as channel utilization and average delay. This makes Blind-ReTx a viable solution for when the feedback channel is unable to offer a reasonable level of reliability. Further, Asym-SAW feedback operation requires stringent $q_0$ adjustment of, e.g., $q_0 < 10^{-4}$ for $P_{\text{out}} < 10^{-5}$. In highly
Table II: Average number of transmission attempt per packet, $\bar{N}$

|                | finite $M$                                                                 | $M \rightarrow \infty$ |
|----------------|---------------------------------------------------------------------------|--------------------------|
| Reg-SAW        | $\sum_{m=1}^{M} p_{e}^{m-1} p_{0}^{m-1} + \sum_{m=1}^{M-1} (p_{e}^{m-1} - p_{e}^{m}) p_{0}^{m-1} p_{1} 1-p_{1}^{M-m} \frac{p_{1}}{p_{1}}$ | $< \frac{\bar{p}_{1} + \bar{p}_{1} p_{1}}{p_{1}(1-p_{1} p_{0})}$ |
| L-Rep-ACK      | $\sum_{m=1}^{M} p_{e}^{m-1} (1 - p_{0}^{L})^{m-1} + \sum_{m=1}^{M-1} (p_{e}^{m-1} - p_{e}^{m}) (1 - p_{0}^{L})^{m-1} (1 - p_{1}^{L})^{1-(1-p_{1}^{L})M-m} \frac{1}{p_{1}^{L}}$ | $< \frac{\bar{p}_{1} + \bar{p}_{1} (1-p_{1}^{L})}{p_{1}^{L}(1-p_{1}^{L})}$ |
| L-ACK-SAW      | $1 + g_{m} X_{L}^{M-1} + g_{m} Y_{L}^{M-1}$                                | $< 1 + p_{e}(1-p_{0}^{L}) + \bar{p}_{e}(1-p_{1}^{L})$ |
|                | $X_{l}^{m} = \bar{p}_{0} \sum_{l=1}^{l} (1 + g_{m} X_{l}^{m-1} + g_{m} Y_{l}^{m-1})$,                                  |                                         |
|                | $Y_{l}^{m} = p_{1} \sum_{l=1}^{l} \bar{p}_{1}^{l-l} (1 + Y_{l}^{m})$,                                                    |                                         |
|                | and, $X_{l}^{0}, Y_{l}^{0} = 0$, $X_{l}^{m}, Y_{l}^{m} = 0$, and $g_{m} = \frac{p_{e}^{M-m+1}}{p_{e}^{M-m}}$               |                                         |
| ReTx-L-ACK     | $\sum_{m=L}^{M} m \eta_{m}$, where,                                        |                                         |
|                | $\eta_{m} = p_{e}^{m} p_{0}^{L} \bar{p}_{0}^{m-L} \frac{(m-1)}{(L-1)} + \sum_{l=1}^{m} (p_{e}^{l-1} - p_{e}^{l}) \rho_{m,l}$, with |                                         |
|                | $\rho_{m,l} = \min\{l-1, L-1\} \frac{p_{0}^{k} p_{1}^{l} p_{1}^{m-k+1} \frac{(m-1)}{(L-1)} \frac{(m-l)}{(L-k-1)}}{p_{0}^{k+l} p_{1}^{m+1} \frac{(L-1)}{(L-k-1)}}$ |                                         |
|                | and, $\rho_{M,l} = \sum_{n=0}^{L-1} \sum_{k=\max\{n-M+1,0\}}^{\min\{l-n, L-1\}} \frac{p_{0}^{k} p_{1}^{l} p_{1}^{n} \frac{(m-k+1)}{(L-k-1)}}{p_{0}^{k+l} p_{1}^{m} \frac{(L-1)}{(L-k-1)} \frac{(m-n)}{n-M+1}}$ |                                         |
| Asym-SAW       | $\sum_{m=1}^{M} p_{e}^{m-1} q_{0}^{m-1} + \sum_{m=1}^{M-1} (p_{e}^{m-1} - p_{e}^{m}) q_{0}^{m-1} q_{1} \frac{1-q_{1}^{M-m}}{q_{1}}$ | $< \frac{q_{1} + \bar{p}_{1} q_{1}}{q_{1}(1-p_{1} q_{0})}$ |
| Blind Retx     | $M$                                                                        | $\infty$                 |
Table III: Average experienced delay, $\bar{T}$, in number of RTT.

|                | assuming one feedback occasion per RTT |
|----------------|----------------------------------------|
| Reg-SAW        | $\bar{N}$                               |
| L-Rep-ACK      | $\bar{N} * L$                           |
| L-ACK-SAW      | $1 + g_M X^{M-1}_L + g_M Y^{M-1}_L$      |
|                | where, $\forall l \in \{1, ..., L\}$ and $\forall m \in \{1, ..., M - 1\}$, |
|                | $X^m_l = \bar{p}_0 \sum_{l=1}^{l} p_0^{l-i} (l - \bar{m} + 1 + g_m X^{m-1}_l + g_m Y^{m-1}_l)$, |
|                | $Y^m_l = p_1 \sum_{l=1}^{l} p_1^{l-i} (1 + Y^m_l)$ |
|                | and, $X^0_l, Y^0_l = 0$, $X^m_0, Y^m_0 = 0$, and $g_m = \frac{p_0^{M-m+1}}{p_0^{M-m}}$ |
| ReTx-L-ACK     | $\bar{N}$                               |
| Asym-SAW       | $\bar{N}$                               |
| Blind Retx     | $M$                                     |

Table IV: cdf of packet delivery latency $\tau$.

|                | $\Pr \{ \tau \leq \text{TTI} + k * \text{RTT} \}$ |
|----------------|-----------------------------------------------------|
| Reg-SAW        | $\bar{p}_0^k (p_e^k - p_{e+1}^k), \ \forall k \in \{0, ..., M - 1\}$ |
| L-Rep-ACK      | $(1 - p_0^n)(p^n_e - p_{e+1}^n), \ n = k * L, \ \forall k \in \{0, ..., M - 1\}$ |
| L-ACK-SAW      | $\sum_{m=\max\{1, k-L+1\}}^{\min\{k, M-1\}} \bar{p}_0^k (p_e^k - p_{e+1}^k) p_0^{k-m} \bar{p}_0^{l-1} \bar{p}_0^{m} (l-1)$, $\forall k \in \{0, ..., M + L - 2\}$ |
| ReTx-L-ACK     | $(p_e^k - p_{e+1}^k)$ for $k \in \{0, ..., L - 1\}$, and $\sum_{\max\{1, k-L+1\}}^{k} (p_e^k - p_{e+1}^k) p_0^{k-m} \bar{p}_0^{m} \bar{p}_0^{k-m} (k)$ for $k \in \{L, ..., M - 1\}$ |
| Asym-SAW       | $\bar{q}_0^k (p_e^k - p_{e+1}^k), \ \forall k \in \{0, ..., M - 1\}$ |
| Blind Retx     | $p_e^k - p_{e+1}^k, \ \forall k \in \{0, ..., M - 1\}$ |
unreliable feedback channel conditions, with \( q_0 \to 0 \), false NAK rate increases drastically (i.e., \( q_1 \to 1 \)) which increases number of transmission attempts resulting in similar performance as Blind-ReTx approach.

Moreover, from Fig. 5 it is observed that reliability performance of \( L \)-Rep-ACK and \( L \)-ACK-SAW approaches are tightly similar in practical range of feedback diversity order \( L \). The downside of increasing feedback diversity order is the increased energy consumption at the receiver to report more than one feedback per packet transmission (i.e., \( \bar{T} \)). In particular, for use cases where battery life-time is of critical importance, less energy consumption over feedback reports is desirable. Thus, it is required to reduce feedback energy consumption while configuring high reliability for the retransmission protocol. This motivates next section of this paper where we propose a variant of the \( L \)-ACK-SAW approach which similarly requires \( L \) observances of ACK for a data packet to be considered as delivered. However, the new solution reduces number
of average feedback occasions used per packet thanks to the proposed backwards composite feedback operation. This way, \( T \) improves compared to \( L \)-ACK-SAW while thanks to the required multiple ACK observance per packet, a higher reliability of operation is expected compared to Reg-SAW.

III. BACKWARDS COMPOSITE FEEDBACK

In this section we propose a composite feedback solution to provide highly-reliable SAW operation in unreliable feedback channel condition, which can be applied to retransmission protocols such as ARQ/HARQ. In the proposed backwards composite feedback (BCF) solution, the aim is to observe a given \( L > 1 \) times ACK for a packet before the packet is labeled reliably as delivered. In order to avoid drastic increase in \( \bar{T} \), in the proposed BCF solution we suggest to repeat the feedback for each packet in a composite manner. We assume that a BCF process has at most \( L \) active packets in its buffers at each time instance. An active packet is identified as a packet that has been transmitted \( m \) times, where \( 1 \leq m < M \), and ACK feedback is observed for it less than \( L \) times. We define composite feedback at the receiver node at time \( i \) as follows, where \( l \) denotes index of the active packets set.

\[
C_i = \&_{l} A_l
\]

(6)

Therefore, an observed composite feedback \( \tilde{C}_i = 1 \) at the transmitter is counted as ACK for all active packets. In the case \( \tilde{C}_i = 0 \) is observed, a retransmission phase cycle starts which attempts on retransmitting active packets one after another following a given order of packets. The retransmission phase then continues until \( \tilde{C} = 1 \) is observed or the maximum transmission attempt is reached for all active packets. The propose BCF-SAW (BCF-SAW) operation at transmitter and receiver nodes is as follows.

A. Operation at the transmitter

Alg. 1 presents the BCF algorithm at the transmitter side. We assume that all the active packets are stored in separate buffers at the transmitter for in case a retransmission is needed. An active packet is then represented by \( \text{Buffer}(l) \) for \( l \in [0, ..., L - 1] \). The variable NDItoggle stores the
Algorithm 1: Operation at the transmitter

**Input**: observed composite feedback $\tilde{C}_i$

**Output**: transmit packet $P_i$; new data indicator NDI$_i$

1. **if** $\tilde{C}_i == 1$ **then**
   2. ACKcounter($l$) + + $\forall l$;
   3. NDI$_{i+1}$ ← toggle(NDI$_i$);
   4. NDItoggle + + mod $L$;
   5. Buffer(NDItoggle) ← get new packet;
   6. ACKcounter(NDItoggle) = 0;
   7. NAKcounter(NDItoggle) = 0;
   8. $P_{i+1}$ ← Buffer(NDItoggle);
   9. TXcountre(NDItoggle) = 1;
10. **clear** Indx;
11. **else**
12. **if** TXcounter($l$) == 0 or $M$ $\forall l$, **then**
13.     **go to** 3
14. **else**
15.     NDI$_{i+1}$ ← NDI$_i$;
16.     NAKcounter($l$) + + $\forall l$;
17.     Indx ← look up reTx index(TXcounter, ACKcounter, NAKcounter);
18.     $P_{i+1}$ ← Buffer(Indx);
19.     TXcountre(Indx) + +;
20. **end**
21. **i + +;**
22. **return** $P_i$, NDI$_i$;
23. **go to** 1;

Index $l$ of the last active packet which was transmitted for the first time (i.e., NDI was toggled for it). When transmitter node observes ACK over the feedback channel it increments counters ACKcounter($l$) by one for all $l$. Then, NDI is toggled and NDItoggle index is incremented by one mod $L$. The updated NDItoggle points either to an empty buffer or to an active packet where ACKcounter(NDItoggle) = $L$. Buffer(NDItoggle) is therefore reset and substituted by a new packet taken from the higher layer application (this process is denoted by function get new packet). Next transmit occasion is then utilized to transmit the newly initiated active packet. A toggle in NDI bit informs the receiver node about transmission of a new packet.

In the case where NAK is observed, the retransmission phase of the operation starts where active packets are retransmitted one after another following a given order until ACK is observed or the maximum transmission attempt is reached for all active packets. The order in which active packets are retransmitted in this phase is given in a look up table that is pre-shared between receiver and transmitter nodes. The look-up table identifies the next active packet index denoted by variable Indx that is to be retransmitted. This process is denoted by function look up.
**Algorithm 2: Operation at the receiver**

```
Input : observed NDI; received packet \( \tilde{P}_i \)
Output: composite feedback \( C_i \)

1. if NDI is toggled then
   2. ACKcounter\((l)\) ++ \( \forall l \in [0, ..., L - 1] \);
   3. NDItoggle ++ mod \( L \);
   4. Buffer(NDItoggle) ← \( \tilde{P}_i \);
   5. RXcounter(NDItoggle) = 1;
   6. ANDItoggle ← decode success(\( \tilde{P}_i \))

else
   8. NAKcounter\((l)\) ++ \( \forall l \);
   9. Indx ← look up reTx index\((RXcounter, ACKcounter, NAKcounter)\);
   10. RXcounter(Indx) += ;
   11. AIndx ← decode success(\( \tilde{P}_i, Buffer(Indx) \));
   12. Buffer(Indx) ← combine(\( \tilde{P}_i, Buffer(Indx) \));

14. \( i += ; \)
15. \( C_i ← A_i \) where \( l = NDItoggle \) or, RXcounter\((l) \) ≠ 0, \( M \);
16. return \( C_i \);
17. go to 1;
```

B. **Operation at the receiver**

Receiver node follows Alg. 2 where firstly it detects whether the received packet is a new transmission or it is retransmission of one of the earlier received active packets. This is done at each time \( i \) by observing NDI\(_i\) signal and comparing it with NDI\(_{i-1}\). The variable NDItoggle ∈ \([0, ..., L - 1]\) store the index of the active packet which is most recently received for the first time. If NDI is detected to be toggled, NDItoggle index at the receiver is incremented by one mod \( L \). Then, Buffer(NDItoggle) is substituted with the newly received packet. Function `decode success` outputs the feedback generated from decoding \( l \)th active packet, denoted using upper case index by \( A_i \). We assume zero chance of error detection failure where the acknowledgement for a packet is generated based on error detection for the packet, e.g., using cyclic redundancy check (CRC).

In case NDI signal is detected as untoggled, the algorithm follows retransmission phase operation where the pre-shared look-up table is used to find the index of the active packet that is being retransmitted (denoted by Indx). Decoding in such case may be based on the received
retransmission and the stored version of the active packet from previous (re)transmission attempts to provide the decoder with combing gain. Similarly, the buffer content may be updated (e.g., in case of $A^{\text{Indx}} = 0$) after combining the two versions of the packet. Composite feedback $C_i$ is generated using $A^l$ for all the active packet indexes $l$ according to (6).

The retransmission phase order of packets follows a pre-shared look-up table. As discussed above we assume that both nodes keep track of the number of transmission attempts and the number of observed ACK and NAK for each active packet. Given the value of these counters the next packet to be retransmitted in case of NAK is found.

C. Example case for $L = 2$

The proposed BCF operation is explained below for the case of $L = 2$, i.e., twice ACK observances required for a packet to be considered as delivered). The cases of larger $L$ will follow a similar approach.

Operation in case of observed composite ACK, $\tilde{C}_i = 1$: As depicted in Fig. 6, two active packets are assumed at the transmitter each having a separate TXcounter and ACKcounter. The process starts by transmitting packet $P_1$ thus, the first feedback occasion only acknowledges decoding status for packet 1, $C_1 = A^1$. Transmitter then initiates the second active packet by transmitting packet $P_2$ in the following transmit occasion. We assume that receiver is notified of the new packet using a single-bit NDI signal.

In the second feedback occasion, receiver composites acknowledgement the two active packets resulting in composite NAK due to decoding failure for $P_2$, $C_2 = A^1 \& A^2 = 0$. The observed composite feedback at time $i = 2$ is however erroneously detected as ACK, i.e., $\tilde{C}_2 = 0$. The observed ACK feedback counts as one ACK for both active packets resulting. As a result, ACKcounter for packet 1 reaches $L = 2$ and the packet is regarded as delivered and thus discarded from BCF-SA W process. Note that for ease of following the illustration, TXcounter blocks in Fig. 6 show the counter value and the corresponding packet number in brackets.

Next, $P_3$ is transmitted and decoded successfully. However, since $A^2 = 0$, the composite feedback at time $i = 3$ is $C_3 = 0$. A second feedback error at time $i = 3$ results in $\tilde{C}_3 = 1$ and as a result $P_2$ is discarded from the transmitter buffer even though it failed in decoding. Such outage case requires $L = 2$ times NAK→ACK errors during the time a packet is in an active packet buffer of the transmitter node.
transmit occasion | 1 | 2 | 3 | 4 | 5  
---|---|---|---|---|---
composite feedback | 1 | 1&2 | 2&3 | 3&4 | 4&5  
feedback observation | 1 | 1&2 | 2&3 | 3&4 | 4&5  
transmitter TXcounter(1) | 1(1) | 1(1) | 1(3) | 1(3) | 1(5)  
transmitter ACKcounter(1) | 1 | 2 | 1 | 2 | 1  
transmitter TXcounter(2) | 0 | 1(2) | 1(2) | 1(4) | 1(4)  
transmitter ACKcounter(2) | 0 | 1 | 2 | 1 | 2  

Figure 6: Backwards feedback bundling operation in case of composite ACK.

Operation in case of observed composite NAK, $\tilde{C}_i = 0$: An observed composite NAK initiates retransmission phase where active packets are retransmitted one after another according to a pre-shared order of packets. NDI remains un-toggled during retransmission phase. The retransmission phase continues until ACK is observed or the transmit counter for all active packets reaches $M$. In Fig. 7 we assume similar events have encountered as in Fig. 6 up to feedback occasion $i = 3$. Let’s assume that at $i = 3$ in Fig. 7 composite feedback is correctly detected, $\tilde{C}_3 = 0$. From transmitter point of view, observed composite NAK may be caused by several events including decoding failure of one of the active packets or feedback channel error. For instance, the observed composite NAK $\tilde{C}_3$ in Fig. 7 may be the result of any of the following events.

- $E1$: $F^1_3 \& S^1_2$ followed by successful feedback detection at $i = 3$
- $E2$: $F^1_2 \& S^1_3$ with successful feedback detection at $i = 3$ and feedback error at $i = 2$
- $E3$: $F^1_2 \& F^1_3$ with successful feedback detection at $i = 3$ and feedback error at $i = 2$
- $E4$: $S^1_2 \& S^1_3$ followed by feedback error at $i = 3$

The likelihood of such events can be evaluated as it was explained in Sec. ?? . E.g., for packet transmission with target $p_e = 0.1$ and feedback channel reliability of $p = 0.001$, $E1$ is the more likely event making $P^3$ the best candidate for retransmission in next transmit occasion. Nevertheless, the retransmission packet order as a function of TXcounter, ACKcounter and NAKcounter can be established prior to start of the communication process and shared between communicating nodes.
In Fig. 7 retransmission of $P_4^3$ is performed at $i = 4$. Due to failure of $P_2^2$, NAK composite feedback $C_4 = 0$ is generated at the receiver node and correctly detected at the transmitter. Therefore, retransmission phase continues and transmitter uses the look-up table to pull the next index of active packet that must be retransmitted. Thus, at time $i = 5$, $P_5^2$ is retransmitted resulting in $S_2^2$.

| transmit occasion | 1 | 2 | 3 | 3 | 2 |
|-------------------|---|---|---|---|---|
| composite feedback| 1 | 1/2| 2/3| 2/3| 2/3|
| feedback occasion | 1 | 1/2| 2/3| 2/3| 2/3|
| transmitter TXcounter(1) | 1(1)| 1(1)| 1(3)| 2(3)| 2(3)|
| transmitter ACKcounter(1) | 1 | 2 | 0 | 0 | 1 |
| transmitter TXcounter(2) | 0 | 1(2)| 1(2)| 1(2)| 2(2)|
| transmitter ACKcounter(2) | 0 | 1 | 1 | 1 | 2 |

Figure 7: Backwards composite feedback operation in case of observed NAK. Feedback error has occurred in the second feedback occasion.

The proposed BCF-SAW uses the same number of feedback occasions per packet transmit occasions as in Reg-SAW in Fig. 1 without the need to increase time diversity of feedback channel. However, each packet is ACKed $L$ times over the feedback channel which in turn increases the reliability of packet delivery.

**IV. NUMERICAL RESULTS**

In this section we evaluate the packet outage probability of the proposed BCF-SAW against the range of feedback channel reliability metrics $p$ and compare it with benchmark approaches introduced in Sec. III. All the results are presented for the case of $M = 4$ for repeated Monte Carlo analysis where $p_e = 0.1$ and the combining gain is modeled by $g$ in $p_e^m = (p_e^{m-1})^g$ for $m > 1$. For the case of ARQ operation, combining gain is set to $g = 1$ while for the case of HARQ operation we assume $g = 1.2$. The retransmission protocols are allowed to transmit only one packet (either initial transmission or retransmission) per transmit occasion. We further
Figure 8: Outage probability for $p_0 = p_1 = p$. The four black-colored markers from top to bottom represent Reg-SAW for ARQ and HARQ and Blind-ReTx for ARQ and HARQ.

adopt the assumption of an error-free NDI detection at the receiver node to solely focus on the effects of unreliable feedback channel. Performance of the proposed BCF-SAW is evaluated for different number of required ACK observances, $L$. We assume a simple retransmission phase packet order where upon observing a composite NAK the last active packet is retransmitted until an ACK is observed. Otherwise, when transmit counter reaches $M$ for the packet retransmission phase order switches to the next last active packet and repeats the same process until all active packets reach $M$ transmission attempts or an ACK is observed.

Best case outage probability for HARQ and ARQ operations reaches $\prod_m p_e^m$ resulting in $4.285e-6$ and $1e-4$ limits respectively as shown in Fig. 8. The proposed BCF-SAW reduces
Figure 9: Average number of feedback occasions utilized per packet packets $\bar{T}$ for $p_0 = p_1 = p$ and combining gain $g = 1.2$.

outage probability by orders of magnitude e.g., for $L = 2$ and $L = 4$ as compared to Reg-SAW even in highly unreliable feedback cases while its outage performance is bounded by $L$-ACK-SAW. The latter performs more reliably because the $L$ observances of ACK are separately received for a given packet and a NAK feedback will trigger retransmission of the same packet. On the other hand, NAK observance in BCF-SA W may be followed by retransmission of a packet other than the failed packet incurring additional feedback occasions which may increase the false ACK rate. The better outage performance of $L$-ACK-SAW and $L$-Rep-ACK is thanks to the increased number of channel uses per packet $\bar{N}$ as shown in Fig. 10. However, the penalty paid for improved reliability by the two latter approaches, as shown in Fig. 9 is an increased average
number of feedback occasions per packet \( \bar{T} \) which is equivalent to the average experienced delay by higher layer application. \( \bar{T} \) increases almost linearly by increasing \( L \) for those two methods resulting in a significantly higher penalty as compared to the proposed BCF-SAW.

In Fig. 11, complementary cumulative density function (ccdf) of packet delivery latency is shown for all the approaches achieving \( P_{\text{out}} \leq 10^{-5} \) in \( R5 \) from Fig. 8. The best case latency performance is achieved using Blind-ReTx and Asym-SAW with \( q_0 = 10^{-5} \). While \( L\text{-ACK-SAW} \) with \( L = 4 \) provides a better latency statistic than BCF-SAW, it fails in the average delay experienced by the higher layer application. This increases number of feedback reporting per packet transmit occasion roughly by \( L \). On the other hand, BCF-SAW uses roughly the same average number of feedback reporting per packet as compared to Reg-SAW while providing higher reliability. By comparison of the presented numerical results in different ultra-reliability operation regions the following observations can be made.

- In fairly reliable feedback channel conditions, e.g., lower \( p \) regime in region \( R4 \), Asym-SAW provides high reliability with low \( \bar{T} \) which makes it a viable choice for only when \( p \) is ideally low.
- In unreliable feedback conditions, e.g., region \( R5 \) and higher \( p \) regime in \( R4 \), BCF-SAW is the most viable solution for ultra-reliable communication with low energy and low cost receiver type where low \( \bar{T} \) is required. For use cases with low latency requirement, \( L\text{-ACK-SAW} \) approach performs better if \( L < M \) however, it requires relaxed limitations on receiver node energy consumption and assuming low traffic channel (i.e., where high \( \bar{T} \) is tolerated). Otherwise, for \( L \geq M \), Blind-ReTx performs more efficiently than \( L\text{-ACK-SAW} \) with less energy consumption for feedback and guaranteed ultra reliability.
- In extremely unreliable feedback channel conditions, e.g., region \( R6 \), Blind-ReTx is the better choice over Asym-SAW, providing similar performance without the need for feedback channel.

V. CONCLUSIONS

We proposed a new method of acknowledging packet delivery for unreliable feedback channel conditions. The proposed method, dubbed BCF-SAW, relies on backwards composite acknowledgement and provides the retransmission protocols with configurable ultra-reliability. It further
Figure 10: Average channel use per packet in number of transmit occasions for $M = 4$, $p_0 = p_1 = p$ and $p_e = 0.1$.

provides the scheduler of the wireless system with new degrees of freedom to configure the communication link in order to meet the desirable reliability requirement even in highly-unreliable feedback channel conditions. The presented numerical analysis show orders of magnitude increase in reliability of the retransmission protocols over the practical range of target block error rate only at the cost of a negligible increase in average experienced packet delay. System-level performance analysis of the proposed method in more realistic multi-user communication systems with time-varying channel conditions will be studied as future work.
Figure 11: ccdf of the packet delivery latency at $p = 2e^{-2}$ with combining gain $g = 1.2$, where $t_k = \text{TTI} + k \ast \text{RTT}$.

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