Uplink HARQ for Cloud RAN via Separation of Control and Data Planes

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Abstract—The implementation of uplink HARQ in a Cloud-Radio Access Network RAN (C-RAN) architecture is constrained by the two-way latency on the fronthaul links connecting the Remote Radio Heads (RRHs) with the Baseband Units (BBUs) that perform decoding. To overcome this limitation, this work considers an architecture based on the separation of control and data planes, in which retransmission control decisions are made at the edge of the network, that is, by the RRHs or User Equipments (UEs), while data decoding is carried out remotely at the BBUs. This solution enables low-latency local retransmission decisions to be made at the RRHs or UEs, which are not subject to the fronthaul latency constraints, while at the same time leveraging the decoding capability of the BBUs.

A system with BBU Hoteling system is considered first in which each RRH has a dedicated BBU in the cloud. For this system, the control-data separation leverages low-latency local feedback from an RRH to drive the HARQ process of a given UE. Throughput and probability of error of this solution are analyzed for the three standard HARQ modes of Type-I, Chase Combining and Incremental Redundancy over a general fading MIMO link. Then, novel user-centric low-latency feedback strategies are proposed and analyzed for the C-RAN architecture, with a single centralized BBU, based on limited “hard” or “soft” local feedback from the RRHs to the UE and on retransmission decisions taken at the UE. The analysis presented in this work allows the optimization of the considered schemes, as well as the investigation of the impact of system parameters such as HARQ protocol type, blocklength and number of antennas on the performance of low-latency local HARQ decisions in BBU Hoteling and C-RAN architectures.

Index Terms—BBU Hoteling, C-RAN, HARQ, Throughput, MIMO, Chase Combining, Incremental Redundancy, Control and Data Planes Separation Architecture.

I. INTRODUCTION

The Cloud-Radio Access Network (C-RAN) is a candidate cellular architecture for 5G systems, which is characterized by the separation of each base station into a Remote Radio Head (RRH) that retains only radio functionalities and a Baseband Unit (BBU) that implements the rest of the protocol stack, including the physical layer. In a C-RAN as seen in Fig. 1(a), in which the BBUs of different RRHs are distinct, with each BBU performing baseband processing for one RRH (see [2]–[5]). In both cases, the connection between an RRH and a BBU is known as fronthaul link.

The BBU Hoteling and C-RAN architectures lower the expenditure needed to deploy and operate dense cellular networks by simplifying the base stations hardware and by enabling flexible upgrading and easier maintenance (see, e.g., [3]–[5]). BBU Hoteling allows limited forms of cooperation to be implemented among base stations in case the BBUs are co-located, particularly in the downlink, by leveraging an X2 interface that may connect the BBUs with one another within the same cloud [5]. Nevertheless, joint baseband decoding in the uplink is generally not feasible with BBU Hoteling, since it requires the exchange of baseband signals among BBUs, rather than user-plane data as allowed by an X2 interface (see e.g., [3]–[5]). In contrast, the C-RAN architecture can also benefit from the statistical multiplexing and interference management capabilities that are made possible by joint baseband processing.

Main Problem: The implementation of the BBU Hoteling and C-RAN architectures needs to contend with the potentially significant latencies needed for the transfer and processing of the baseband signals on the fronthaul links to and from the BBU(s) [6]. The communication protocols that are most directly affected by fronthaul delays are the Automatic Repeat Request (ARQ) and Hybrid ARQ (HARQ) protocols at layer 2. In fact, in a conventional cellular network, upon receiving a codeword from an UE, the local base station performs decoding, and, depending on the decoding outcome, feeds back an Acknowledgment (ACK) or a Negative Acknowledgment (NACK) to the UE. In contrast, with BBU Hoteling or C-RAN, as illustrated in Fig. 2 the outcome of decoding at the BBU may only become available at the RRHs after the time required to perform decoding locally.
Fronthaul latency is unavoidable in conventional BBU Hoteling or C-RAN architectures. This can significantly affect the performance of retransmission protocols. For instance, in LTE with frequency division multiplexing, the feedback latency should be less than 3 ms in order not to disrupt the operation of the system. We also refer to [9], [10] for a discussion on the latency on HARQ and ARQ protocols in C-RAN architectures.

A Solution Based on the Separation of Control and Data Planes: Fronthaul latency is unavoidable in conventional BBU Hoteling and C-RAN architectures in which the RRHs only retain radio functionalities. Nevertheless, alternative functional splits are currently being investigated whereby the RRH may implement some additional functions [4], [8], [11], [12]. In this work, we consider a functional split that enables the separation of control and data planes associated with the HARQ protocol, with the aim of alleviating the problem of fronthaul latency. We note that the approach studied here can be seen as an instance of the more general principle of control and data planes, which is a positive integer, albeit at the cost of possibly reducing the throughput. Of the mentioned 3 ms latency, it has been recently specified that the one-way transport delay on the fronthaul should be no larger than around 400 μs [6].

Fig. 2. Conventional HARQ in BBU Hoteling or C-RAN systems. The numbers indicate the sequence of events associated with a transmission. Fronthaul latency is associated with the fronthaul transmissions at steps 2 and 4 and with the part of BBU processing at step 3 needed to encode and decode transmissions on the fronthaul links. The cross-links in the uplink carry interference in a BBU Hoteling system and useful signals in a C-RAN. The dashed cross-links in the ACK/NAK feedback path are used only in the C-RAN architecture.

In particular, we investigate an architecture in which retransmission control decisions are made at the edge of the network, that is, by the RRHs or UEs, while decoding of data-plane information is carried out remotely at the BBUs as in conventional BBU Hoteling or C-RAN systems. This separation of HARQ control at the edge and data-plane processing at the BBU(s) has the following advantages: (i) retransmission control is not subject to the fronthaul latency constraints; (ii) given that data-plane processing is performed at the BBU(s), the complexity of the RRHs can be kept below that of a conventional base station; (iii) the benefits of joint baseband processing of data-plane information at the BBU of a C-RAN system in terms of spectral efficiency are maintained.

The implementation of low-latency local control of the retransmission process at the edge is made possible by an RRH-BBU functional split whereby each RRH can perform synchronization and resource demapping [8] so as to perform the estimation of uplink channel state information (CSI). To elaborate, consider first a BBU Hoteling system. As proposed in [8] and in [14], based on the available CSI, an RRH can attempt to predict whether successful or unsuccessful decoding is expected to occur at the BBU for the symbol received from a given UE. Accordingly, it can feed back an ACK/NAK message without waiting to be notified about the actual decoding outcome at the BBU and without running the channel decoder on the data-plane information, which is implemented only at the BBU. Fig. 3 presents an illustration of the outlined low-latency approach.

The local feedback approach under discussion introduces possible errors due to the mismatch between the local decision at the RRH and the actual decoding outcome at the BBU. Indeed, the RRH may request an additional retransmission for a packet that the BBU is able to decode, or acknowledge correct reception of a packet for which decoding eventually fails at the BBU, hence causing a throughput degradation.

In a C-RAN, which is characterized by joint baseband processing across multiple RRHs, the outlined approach based on control at the edge is complicated by the fact that the CSI between the UE and each RRH is not known to other RRHs. Therefore, it is not possible for the RRHs to directly

2By interleaving multiple HARQ processes, as discussed in [8], the tolerated latency can be increased to 3 + φs ms, where n is a positive integer, albeit at the cost of possibly reducing the throughput. Of the mentioned 3 ms latency, it has been recently specified that the one-way transport delay on the fronthaul should be no larger than around 400 ms [6].

3While the computational complexity of the operations carried out at the BBUs is not a primary concern for the BBU Hoteling or C-RAN architectures, it is noted that the solutions proposed here based on the separation of control and data planes, do not increase the complexity of the BBU as compared to that of a conventional system.

4In an OFDM system, such as LTE, this requires also the implementation of an FFT block.
agree on HARQ control decisions, making the local feedback mechanism proposed in [8] and [14] not applicable.

**Main contributions:** The main contributions of this paper are summarized as follows.

- For BBU Hoteling, we analyze throughput and probability of error of the outlined approach based on control and data separation for the three standard HARQ modes of Type-I (TI), Chase Combining (CC) and Incremental Redundancy (IR) over a multi-antenna, or MIMO, link with coding blocks (packets) of arbitrary finite length. This is done by leveraging recently derived finite-blocklength capacity bounds [15]. As a result, unlike the existing literature [8] and [14], the analysis allows the investigation of the impact of system parameters such as HARQ protocol type, blocklength and number of antennas. We note that the analysis in [14] focuses on the throughput of single-antenna links in a BBU Hoteling with HARQ-IR and is based on an error exponent framework, which is known to provide an inaccurate evaluation of the probability of error in the practical finite-blocklength regime [15, Eq. (54)] [16, Sec. 1.2 and Sec. 1.3].

- We propose and analyze user-centric low-latency feedback schemes for C-RAN systems based on the control and data separation architecture. According to the proposed techniques, limited-feedback information is sent from each RRH to an UE in order to allow the latter to make a low-latency local control decision about the need for a retransmission. A “hard feedback” approach is first proposed that directly generalizes the BBU Hoteling scheme described above and requires a one-bit feedback message from each RRH. Then, a “soft feedback” strategy is proposed in which the UE decision is based on multi-bit feedback from the RRHs, consisting of quantized local CSI.

The rest of the paper is organized as follows. In Sec. II the system model for BBU Hoteling and C-RAN systems is introduced. Sec. III details the principles underlying the proposed low-latency local feedback solutions for BBU Hoteling and C-RAN systems. The metrics used to evaluate the performance of the proposed schemes and some preliminaries are discussed in Sec. IV. In Sec. V and Sec. VI the analysis of BBU Hoteling and C-RAN strategies is presented. In Sec. VII the numerical results are provided, and Sec. VIII concludes the paper.

**Notation:** Bold letters denote matrices and superscript $H$ denote Hermitian conjugation. ${\mathcal{CN}}(\mu, \sigma^2)$ denotes a complex normal distribution with mean $\mu$ and variance $\sigma^2$; and $\chi_k^2$ a Chi-Squared distribution with $k$ degrees of freedom. $f_A(x)$ and $F_A(x)$ represent the probability density function and the cumulative distribution function of a distribution $A$ evaluated at $x$, respectively. $\mathbf{A} = \text{diag}([A_1, \ldots, A_n])$ is a block diagonal matrix with block diagonal given by the matrices $[A_1, \ldots, A_n]$. The indicator function $\mathbf{1}(x)$ equals 1 if $x = \text{true}$ and 0 if $x = \text{false}$.

II. SYSTEM MODEL

We study the uplink of both BBU Hoteling and C-RAN systems as illustrated in Fig. 1. In this section, we detail system model and performance metrics.

**A. System Model**

As seen in Fig. 1, each RRH is connected by means of orthogonal fronthaul links to a dedicated BBU for BBU Hoteling and to a single BBU for C-RAN systems. The BBUs perform decoding, while the RRHs have limited baseband processing functionalities that allow resource demapping and the inference of CSI as discussed in Sec. II and further detailed below. Different UEs are served in distinct time-frequency resources, as done for instance in LTE, and hence we focus here on the performance of a given UE.

Each packet transmitted by the UE contains $k$ encoded complex symbols and is transmitted within a coherence time/frequency interval of the channel, which is referred to as slot. The transmission rate of the first transmission of an information message is defined as $r$ bits per symbol, or equivalently, bit/s/Hz, so that $kr$ is the number of information bits in the information message.

Each transmitted packet is acknowledged via the transmission of a feedback message by the RRHs. We assume that these feedback messages are correctly decoded by the UE. We will first assume that messages are limited to binary positive or negative acknowledgments, i.e., ACK or NAK messages, in Sec. III-A and will consider the more general case in which feedback messages may consist of $b \geq 1$ bits in Sec. III-B. The same information message may be transmitted for up to $n_{\text{max}}$ successive slots using standard HARQ protocols such as TI, CC and IR, to be recalled in Sec. III.

The UE is equipped with $m_t$ transmitting antennas, while $m_{r,l}$ receiving antennas are available at the $l$th RRH. The received signal for any $n$th slot at the $l$th RRH can be expressed as

$$y_{l,n} = \sqrt{\frac{s}{m_t}} \mathbf{H}_{l,n} \mathbf{x}_n + \mathbf{w}_{l,n},$$

where $s$ measures the average SNR per receive antenna: $\mathbf{x}_n \in \mathbb{C}^{m_t \times 1}$ represents the symbols sent by the transmit antennas at a given channel use, whose average power is normalized as $\mathbb{E}[\|\mathbf{x}_n\|^2] = 1$; $\mathbf{H}_{l,n} \in \mathbb{C}^{m_{r,l} \times m_t}$ is the channel matrix, which is assumed to have independent identically distributed (i.i.d.) ${\mathcal{CN}}(0, 1)$ entries (Rayleigh fading); and $\mathbf{w}_{l,n} \in \mathbb{C}^{m_{r,l} \times 1}$ is an i.i.d. Gaussian noise vector with ${\mathcal{CN}}(0, 1)$ entries. The channel matrix $\mathbf{H}_{l,n}$ are independent for different RRHs $l \in \{1, ..., L\}$ and also change independently in each slot $n$. Moreover, they are assumed to be known to the $l$th RRH and to the BBU. We assume the use of Gaussian codebooks with an equal power allocation across the transmit antennas, although the analysis could be extended to arbitrary power allocation and antenna selection schemes.

**B. Performance Metrics**

The main performance metrics of interest are as follows.

- **Throughput $T$:** The throughput measures the average rate, in bits per symbol, at which information can be successfully delivered from the UE to the BBU;

- **Probability $P_s$ of success:** The metric $P_s$ measures the probability of a successful transmission within a given HARQ session, which is the event that, in one of the
III. LOW-LATENCY LOCAL FEEDBACK

In this section, we introduce the key working principles underlying low-latency local feedback solutions for BBU Hoteling and C-RAN.

A. RRH-Based Low-Latency Local Feedback for BBU Hoteling

In a BBU Hoteling architecture, each pair of RRH and corresponding BBU operates as a base station in a conventional cellular system [3]-[4]. Therefore, an UE is assigned to a specific RRH-BBU pair by following standard user association rules. For BBU Hoteling, as in [14], we can then focus on a single RRH, i.e., $L = 1$, with the understanding that the noise term in (1) may account also for the interference from UEs associated to other RRH-BBU pairs. When studying BBU Hoteling systems, we hence drop the subscript $l$ indicating the RRH index.

The low-latency local feedback scheme for BBU Hoteling, first proposed in [8], is illustrated in Fig. 4. At each transmission attempt $n$, the RRH performs resource demapping and obtains CSI about the channel $H_{nl}$. The Modulation and Coding Scheme (MCS) used for data transmission is decided by the BBU during scheduling and can be sent by the BBU to the RRH. Note that the MCS amounts here to the rate $r$ and packet length $k$. Based on this information, the RRH can compute the probability of error $P_{e}(r, k, \{H_{nl}\}_{l=1}^{n})$ for decoding at the BBU, where we emphasized the possible dependence of the probability of error $P_{e}$ on all channel matrices $[H_1, \ldots, H_n]$ corresponding to prior and current transmission attempts. We note that the probability $P_{e}$ may be read on a look-up table or obtained from some analytical approximations as discussed in the next section. As proposed in [14], if the decoding error probability $P_{e}(r, k, \{H_{nl}\}_{l=1}^{n})$ is smaller than a given threshold $P_{th}$, the RRH sends an ACK message to the UE, predicting a positive decoding event at the BBU; while, otherwise, a NAK message is transmitted, that is,

$$P_{e}(r, k, \{H_{nl}\}_{l=1}^{n}) \overset{\text{ACK}}{\lesssim} P_{th}. \quad (2)$$

As we will discuss in Sec. VII the optimization of the threshold $P_{th}$ needs to strike a balance between the probability of success $P_{s}$, which would call for a smaller $P_{th}$ and hence more retransmissions, and the throughput $T$, which may be generally improved by a larger $P_{th}$, resulting in the transmission of new information.

B. User-Centric Low-Latency Local Feedback for C-RAN

In C-RAN, unlike BBU Hoteling systems, a BBU jointly processes the signals received by several connected RRHs (Fig. 1-(b)). Therefore, a UE-RRH assignment step is not needed as the BBU performs decoding based on the signals received from all connected RRHs. The development of a local feedback solution based on the implementation of control decision at the edge is hence complicated for C-RAN by the fact that the BBU decoding error probability $P_{e}(r, k, \{H_{nl}\}_{l=1}^{n})$ depends on the CSI $\{H_{nl}\}_{l=1}^{n}$ between the UE and all RRHs, while each RRH $l$ is only aware of the CSI $\{H_{l,i}\}_{i=1}^{n}$ between the UE and itself. Therefore, the decoding error probability $P_{e}(r, k, \{H_{nl}\}_{l=1}^{n})$ cannot be calculated at any RRH as instead done for BBU Hoteling.

To overcome this problem, in this paper, we propose a user-centric low-latency local HARQ mechanism, whereby the UE collects limited-feedback messages from the RRHs to make a local control decision on whether another transmission attempt is necessary.
Local feedback is received. NAK message and to stop retransmissions if at least one ACK according to the same rule used in BBU Hoteling system, i.e.,
\[ P_e(r, k, \{ \mathbf{H}_{l,n} \}_{l \leq n}) \leq P_{\text{NAK}}. \]  

The UE decides to retransmit the packet if all RRHs return a NAK message and to stop retransmissions if at least one ACK is received.

2) Soft Feedback: The soft feedback schemes aims at leveraging multi-bit feedback messages, composed of \( b \geq 1 \) bits, from each RRH to the UE. The key idea here is that the UE can estimate the decoding error probability \( P_e(r, k, \{ \mathbf{H}_{l,n} \}_{l \leq n}) \) of the BBU upon receiving information from each RRH \( l \) about the local CSI \( \mathbf{H}_{l,n} \). To this end, in the soft feedback scheme, each RRH quantizes its own CSI \( \mathbf{H}_{l,n} \) by using vector quantization \[ \mathbf{H}_{l,n} \rightarrow \mathbf{H}_{l,n}^\prime \] with \( b \) bits and sends the quantized CSI \( \Gamma(\mathbf{H}_{l,n}) = \mathbf{H}_{l,n}^\prime \) to the UE via a \( b \)-bit feedback message. Then, the UE performs a retransmission if the estimated decoding error probability \( P_e(r, k, \{ \mathbf{H}_{l,n} \}_{l \leq n}) \), with \( \mathbf{H}_{l,n}^\prime \) collecting all the quantized matrices \( \mathbf{H}_{l,n}^\prime \) for \( l \in \{1, ..., L\} \), is larger than a threshold \( P_{\text{th}} \) and stop retransmission otherwise, as in
\[ P_e(r, k, \{ \mathbf{H}_{l,n} \}_{l \leq n}) \leq P_{\text{NAK}}. \]

IV. PERFORMANCE CRITERIA AND PRELIMINARIES

In this section, we discuss the general approach that will be followed to evaluate throughput and probability of success for the considered schemes in BBU Hoteling and C-RAN systems. We also discuss the comparison in terms of average latency between the conventional C-RAN implementation and the considered feedback schemes.

A. Throughput and Probability of Success

To start, let us denote as RTX\(_n\) the event that a retransmission decision is made for all the first \( n \) transmission attempts of an information message. In a similar manner, we define as STOP\(_n\) the event that a decision is made to stop the retransmission of a packet at the \( n\)th attempt, and hence \( n - 1 \) retransmission attempts have been performed before. As we discussed in Sec. [III] these decisions are made at the RRH for the low-latency local feedback scheme in BBU Hoteling and at the UE in the proposed user-centric low-latency strategies for C-RAN. By definition, the probabilities of these events satisfy the equality
\[ P(\text{STOP}_n) = P(\text{RTX}_{n-1}) - P(\text{RTX}_n). \]

In case of ideal feedback from the BBU, a STOP/RTX event reflects correct/incorrect decoding at the BBU, whereas this is not the case for the local feedback schemes due to the possible mismatch between the RRHs’ or users' decisions and the decoding outcome at the BBU. In particular, there are two types of error as summarized in Table I. In the first type of error, the transmitted packet is not decodable at the BBU, but a STOP decision is made by the local feedback scheme. This type of mismatch causes a failure of the HARQ process, hence adding to the probability of error, or, equivalently reducing the probability of success. In practice, this event may need to be dealt with by higher layers. In the second type of error, the received packet is decodable at the BBU, but an RTX decision is made. In this case, the UE either performs an unnecessary retransmission, hence increasing the number \( N \) of transmissions, or, in case the maximum number \( n_{\text{max}} \) of retransmissions has already been carried out, the HARQ session fails.

We now elaborate on the calculation of the throughput \( T \) and probability of success \( P_s \) for both the local feedback schemes and reference ideal case of zero-delay feedback from the BBU. We emphasize that for local feedback, we will consider both the case of zero-delay feedback from the BBU is given as
\[ T = E[N]/(n_{\text{max}})! \]
where we recall that \( r \) is the transmission rate, and the random variable \( N \) denotes the number of transmission attempts for a given information message. The average number of transmissions can be computed directly as
\[ E[N] = \sum_{n=1}^{n_{\text{max}}-1} nP(\text{STOP}_n) + n_{\text{max}}P(\text{RTX}_{n_{\text{max}}-1}). \]

Moreover, the probability of a successful transmission for the case of zero-delay feedback from the BBU is given as
\[ P_s = 1 - P(\text{RTX}_{n_{\text{max}}}). \]

Instead, with local feedback, a transmission is considered as successful if a decision is made to stop the retransmission of a packet within one of the \( n_{\text{max}} \) allowed transmissions attempts and if the BBU can correctly decode. Hence, by the law of total probability, the probability of success \( P_s \) can be written as
\[ P_s = \sum_{n=1}^{n_{\text{max}}} P(D_n|\text{STOP}_n)P(\text{STOP}_n), \]
where \( D_n \) is the event that the BBU can correctly decode at the \( n \)th transmission.

In summary, in order to evaluate the throughput, we use (5)-(7) for both ideal and local feedback; while, for the probability of success \( P_s \), we use (8) for the case of ideal feedback and (9) for local feedback. Therefore, to compute both metrics, we only need to calculate the probabilities \( P(\text{RTX}_n) \), for both ideal and local feedback, and the probabilities \( P(D_n|\text{STOP}_n) \) for local feedback, with \( n = 1, ..., n_{\text{max}} \). We will use this

| BBU decoding outcome | Local feedback decision | Consequence |
|----------------------|-------------------------|-------------|
| Undecodable          | STOP                    | • HARQ session failure |
|                      |                         | • Delays due to higher-layer protocols |
| Decodable            | RTX                     | • HARQ retransmission |
|                      |                         | • HARQ session failure if last transmission |
approach in the next two sections for BBU Hoteling and C-RAN systems.

B. Gaussian Approximation

Throughout this paper, we adopt the Gaussian approximation proposed in [20], based on the work in [13], to evaluate the probability $P_c(r, k, H)$ of decoding error for a transmission at rate $r$ in a slot of $k$ channel uses when the channel matrix is $H$. This amounts to

$$P_c(r, k, H) = Q \left( \frac{C(H) - r}{\sqrt{V(H)k}} \right), \quad (10)$$

where we have defined

$$C(H) = \sum_{j=1}^{m_{rt}} \log_2 \left( 1 + \frac{s_j \lambda_j}{m_{rt}} \right)$$

and

$$V(H) = \left( m_{rt} - \sum_{j=1}^{m_{rt}} \frac{1}{1 + \frac{s_j \lambda_j}{m_{rt}}} \right) \log_2 e,$$ \quad (11)

with $m_{rt} = \min(m_r, m_t)$; $\{ \lambda_j \}_{j=1,...,m_{rt}}$ being the eigenvalues of the matrix $H^H H$; and $Q(\cdot)$ being the Gaussian complementary cumulative distribution function. Expressions obtained by means of the Gaussian approximation (10) will be marked for simplicity of notation as equalities in the following.

For future reference, we note that we have the limit

$$\lim_{k \to \infty} P_c(r, k, H) = \begin{cases} 1 & \text{if } C(H) < r \\ 0 & \text{if } C(H) > r \end{cases} \quad (12)$$

in the asymptotic regime of large blocklengths.

C. Average Latency

The comparison between the latency of the conventional BBU Hoteling and C-RAN implementations of HARQ and the approach proposed in this paper, which is based on the separation of data and control planes, depends on the specific fronthaul transport latency in the system of interest. To elaborate, we define as $L_f$ the two-way latency for fronthaul transport and processing at the BBU as measured in terms of number of transmission slots. Furthermore, we neglect for simplicity the time required to transmit ACK/NACK messages in the downlink, although this could be easily included as a common term in all latency expressions. The overall average latency $D_c$ of the conventional HARQ implementation in BBU Hoteling and C-RAN is then given as

$$D_c = E[N](1 + L_f), \quad (13)$$

which is measured in terms of number of transmission slots, where we recall that $N$ is the number of retransmissions of the HARQ protocol. The average latency (13) follows since each retransmission requires one time slot for uplink transmission and $L_f$ time slots for two-way fronthaul transmission and BBU processing. In contrast, the average latency of the proposed approach can be approximated as

$$D_s = E[N], \quad (14)$$

since each retransmission can be immediately acknowledged by the RRHs without having to wait for feedback from the BBU. In this regard, we also recall that the processing needed at the RRHs with local feedback is minimal, since it does not entail any decoding, and hence the corresponding latency is much smaller than the processing time needed at the BBU to decode the data packet. From (13) and (14), the ratio of the average latencies for the two implementations is $D_c/D_s = 1 + L_f$.

While our work is not tied to a specific standard or system, current standardization efforts and industry white papers have reported the two-way fronthaul latency $L_f$ to consist of a two-way fronthaul transport latency of around 0.5 ms for single-hop fronthaul links [6] and of a BBU processing time of around 2.3-2.6 ms [21, p.38]. As a result, the two-latency $L_f$, for time slots of duration 1 ms, is no smaller than 3 and potentially much larger, e.g., in the presence of a multihop fronthaul architecture (see also [9]). As a result, the ratio $D_c/D_s$ can be of the order of 4 or larger, showing the significant latency reduction achievable via the proposed approach.

V. ANALYSIS OF RRH-BASED LOW-LATENCY LOCAL FEEDBACK FOR BBU HOTELING

In this section, we analyze the performance in terms of throughput and probability of success of the low-latency local feedback scheme for BBU Hoteling as introduced in Sec. III-A. We focus separately on the three standard modes of HARQ-TI, CC and IR, in order of complexity [22]. We recall that, in the considered low-latency scheme, a decision to stop retransmissions is made by the RRH by sending an ACK message, while a retransmission is decided by the transmission of a NAK message. We define as ACK$_n$ the event that an ACK message is sent at the $n$th transmission attempt and as NAK$_n$ the event that a NAK message is sent for all the first $n$ transmissions. Therefore, in applying the analytical expression introduced in the previous section, we can focus on the evaluation of the probabilities $P(\text{RTX}_n) = P(\text{NAK}_n)$ and $P(\text{RTX}_n | \text{STOP}_n) = P(\text{NAK}_n | \text{ACK}_n)$ in order to calculate throughput and probability of success. Throughout, we use the Gaussian approximation for the probability of error discussed in Sec. IV-B.

A. HARQ-TI

With HARQ-TI, the same packet is retransmitted by the UE upon reception of a NAK message until the maximum number $n_{\text{max}}$ of retransmissions is reached or until an ACK message is received. Moreover, decoding at the BBU is based on the last received packet only. HARQ-TI is hence a standard ARQ strategy [7].

1) Ideal Feedback: For reference, we first study the ideal case in which zero-delay feedback is available directly from BBU. Using the approximation (10) and averaging over the channel distribution, the approximate probability of an erroneous decoding at the BBU at the $n$th retransmission is given
by $E \{P_e(r, k, H_n)\}$. Accordingly, since with HARQ-TI the BBU performs decoding independently for each slot, we obtain

$$P(\text{NAK}_n) = (E \{P_e(r, k, H)\})^n. \quad (15)$$

As discussed, throughput and the probability of success now can be calculated as (2)-(4) and (5), where the throughput can be simplified as

$$T = r \left(1 - E \{P_e(r, k, H)\}\right). \quad (16)$$

The average in (16) can be computed numerically based on the known distribution of the eigenvalues of the Wishart-distributed matrix $H^TH$, see [23] Theorem 2.17. As an important special case, for a SISO link ($m_t = m_r = 1$), we have $|H|^2 \sim X_2^2$ and hence

$$E \{P_e(r, k, H)\} = \int_0^\infty P_e(r, k, \sqrt{x})x f_{X_2^2}(x)dx. \quad (17)$$

2) Local Feedback: With local feedback, as discussed, at each transmission attempt $n$, the RRH estimates the current channel realization $H_n$ and decides whether it expects the BBU to decode correctly or not by comparing the probability of error by using the following rule (2), which reduces to

$$P_e(r, k, H_n) \leq P_{\text{th}}, \quad (18)$$

since decoding is done only based on the last received packet. We observe that, in the case of a single antenna at the transmitter and/or the receiver, the rule (18) only requires the RRH to estimate the SNR $s_j|H_n|^2/m_r$.

The quantities that are needed to calculate the performance metrics under study can be then directly obtained from their definitions as

$$P(\text{D}_n|\text{ACK}_n) = 1 - E \{P_e(r, k, H)\} |P_e(r, k, H) \leq P_{\text{th}}\} \quad (19)$$

and

$$P(\text{NAK}_n) = (P \{P_e(r, k, H) > P_{\text{th}}\})^n. \quad (20)$$

As discussed, (19) and (20) can be obtained by averaging over the distribution of the eigenvalues of $H^TH$. As an example, for a SISO link, we obtain

$$P(\text{D}_n|\text{ACK}_n) = 1 - F_{X_2^2}(\gamma(P_{\text{th}})) \int_0^\infty P_e(r, k, \sqrt{x})x f_{X_2^2}(x)dx \quad (21)$$

and

$$P(\text{NAK}_n) = \left(F_{X_2^2}(\gamma(P_{\text{th}}))\right)^n, \quad (22)$$

where $\gamma(P_{\text{th}})$ is calculated by solving the non-linear equation

$$P_e \left(r, k, \sqrt{\gamma(P_{\text{th}})}\right) = P_{\text{th}}, \quad (23)$$

e.g., by means of bisection.

B. HARQ-CC

With HARQ-CC, every retransmission of the UE consists of the same encoded packet as for TI. However, at the $n$th transmission attempt, the BBU uses maximum ratio combining (MRC) of all the $n$ received packets in order to improve the decoding performance. For HARQ-CC, we only consider here a SISO link. This is because MRC requires to compute the weighted sum of the received signals across multiple transmission attempts, where the weight is given by the corresponding scalar channel for a SISO link. Note that SIMO and MISO links could also be tackled in a similar way by considering weights obtained from the effective scalar channels, although we do not explicitly consider these cases in the paper. Due to MRC, at the $n$th retransmission, the received signal can be written as

$$\bar{y}_n = \sum_{i=1}^n H_{r,k}^* y_i / S_n, \quad (24)$$

or equivalently as

$$\bar{y}_n = \bar{S}_n x + \bar{w}_n, \quad (25)$$

where $y_i$ is the $n$th received packet, the noise $\bar{w}_n$ is distributed as $CN(0,1)$ and the effective channel gain of the combined signal is given by $\bar{S}_n = \sqrt{\sum_{i=1}^n |H_i|^2}$.

1) Ideal Feedback: The probability that the BBU does not decode correctly when the effective SNR is $\bar{S}_n^2$ is given as $P_e(\bar{r}, \bar{k}, \bar{S}_n)$. Let $\bar{D}_n$ denote the event that the $n$th transmission is not decoded correctly at the BBU. The probability of the event $\text{NAK}_n$ is then given as $P(\text{NAK}_n) = P(\bigcap_{j=1}^n \bar{D}_j)$, which can be upper bounded, using the chain rule of probability, as

$$P(\text{NAK}_n) \leq P(\bar{D}_n) \prod_{j=1}^n P(\bar{D}_{n-j}|\bar{D}_j) \leq P(\bar{D}_n) = E \{P_e(\bar{r}, \bar{k}, \bar{S}_n)\}. \quad (26)$$

The usefulness of the bound (26) for small values of $k$ will be validated in Sec. [VII] by means of a comparison with Monte Carlo simulations. We also refer to [24] where the same bound was proposed as an accurate approximation of the probability of error for HARQ-CC. We note that the inequality (26) is asymptotically tight in the limit of a large blocklength, since the limit $P(\bar{D}_n) \prod_{j=1}^n \bar{D}_j \rightarrow 1$ as $k \rightarrow \infty$ holds for a fixed $r$ due to (12) and to the inequality $\bar{S}_n \geq \bar{S}_m$ for $n \geq m$.

The usefulness of the bound (26) for small values of $k$ will be validated in Sec. [VII] by means of a comparison with Monte Carlo simulations. Since the effective SNR is distributed as $\bar{S}_n^2 = \sum_{i=1}^n |H_i|^2 \sim X_2^2$, the bound (26) can be calculated as

$$P(\text{NAK}_n) \leq \int_0^\infty P_e(r, k, \sqrt{x})x f_{X_2^2}(x)dx. \quad (27)$$

2) Local Feedback: With local feedback, the RRH decision is made according to the rule $P_e(r, k, \bar{S}_n) \leq P_{\text{th}}$, for a threshold $P_{\text{th}}$ to be optimized. Similar to (19) and (20), we can compute the probabilities

$$P(\text{D}_n|\text{ACK}_n) = 1 - E \left[P_e(r, k, \bar{S}_n)\right] \left[P_e(r, k, \bar{S}_{n-1}) > P_{\text{th}}\right] \quad (28)$$

and

$$P(\text{NAK}_n) = P[P_e(r, k, \bar{S}_n) > P_{\text{th}}]. \quad (29)$$

Note that in (28), (29) we used the fact that, if the condition $P_e(r, k, \bar{S}_n) > P_{\text{th}}$ holds, then we also have the inequality $P_e(r, k, \bar{S}_i) > P_{\text{th}}$ for all the indices $i < n$ due to the
monotonicity of the probability $P_e(r, k, S)$ as a function of $S$. Furthermore, noting that we can write $S_n^2 = S_{n-1}^2 + |H_n|^2$, where $S_{n-1}^2 \sim \chi^2_{2n-2}$ and $|H_n|^2 \sim \chi^2_2$ are independent, from (28) and (29), we have

$$
P(D_n|\text{ACK}) = 1 - E \left[ P_e(r, k, S_n) \left\{ S_n^2 < \gamma(P_{th}) \right\} \right]
\bigcap \left\{ S_n^2 + |H_n|^2 \geq \gamma(P_{th}) \right\}

= 1 - \frac{1}{\Delta(\gamma(P_{th}))} \int_0^{\gamma(P_{th})} \int_{\gamma(P_{th}) - y}^{\infty} P_e(r, k, \sqrt{x + y}) f_{\chi^2_2}(x) f_{\chi^2_{2n-2}}(y) dx dy
$$

and $P(\text{NAK}_n) = F_{\chi^2_2}(\gamma(P_{th}))$, where

$$\Delta(\gamma(P_{th})) = \int_0^{\gamma(P_{th})} \int_{\gamma(P_{th}) - y}^{\infty} f_{\chi^2_2}(x) f_{\chi^2_{2n-2}}(y) dx dy.$$

### 3. HARQ-IR

With HARQ-IR, the UE transmits new parity bits at each transmission attempt and the BBU performs decoding based on all the received packets.

1) Ideal Feedback: With HARQ-IR, a set of $n$ transmission attempts for a given information message can be treated as the transmission over $n$ parallel channels (see, e.g., [19]), and hence the error probability at the $n$th transmission can be computed as $P_e(r, k, H_n)$ where $H_n = \text{diag}(|H_1|, \ldots, |H_n|)$ [20]. Moreover, following the same argument as [26], the decoding error at the $n$th transmission can be upper bounded as

$$P(\text{NAK}_n) \leq P(\tilde{D}_n) = E \left[ P_e(r, k, H_n) \right],$$

which is tight for large values of $k$ due to [12]. This can be computed using the known distribution of the eigenvalues of the matrices $H_i^2 H_i$ and the independence of the matrices $H_i$ for $i = 1, \ldots, n$. For instance in the SISO case, we get

$$P(\text{NAK}_n) \leq \int_0^{\infty} \cdots \int_0^{\infty} P_e(r, k, \text{diag}(\sqrt{x_1}, \ldots, \sqrt{x_n})) \prod_{i=1}^n f_{\chi^2_2}(x_i) dx_1 \cdots dx_n.$$

2) Local Feedback: With local feedback, at the $n$th retransmission, the RRH sends feedback to the UE according to the rule $P_e(r, k, H_n) \leq \text{ACK}$. Due to the monotonicity of the probability $P_e(r, k, H_n)$ as a function of each eigenvalue, we have that the probability $P_e(r, k, H_n)$ is no larger than $P_e(r, k, H_{n-1})$. Therefore, similar to CC, we can calculate

$$P(D_n|\text{ACK}) = 1 - E \left[ P_e(r, k, H_n) | A(P_{th}) \right] \int_{\gamma(P_{th})}^{\infty} f_{\chi^2_2}(x) f_{\chi^2_{2n-2}}(y) dx dy
$$

and $P(\text{NAK}_n) = P(\text{ACK}) > P_{th}$.

### VI. ANALYSIS OF USER-CENTRIC LOW-LATENCY LOCAL FEEDBACK FOR C-RAN

In this section, we turn to the analysis of the user-centric low-latency local feedback schemes introduced in Sec. II-B for C-RAN. Throughout, we focus on HARQ-IR for its practical relevance, see, e.g., [17]. Furthermore, we consider the case where each RRH has only one receiving antenna, i.e., $m_r = 1$ for $l = 1, \ldots, L$. Extensions to other HARQ protocols and to scenarios with large number of antennas at the RRHs are possible by following similar arguments as in the previous sections and will not be further discussed here. We recall that in a C-RAN with local feedback, the retransmission decisions are made at the UE based on feedback from the RRHs. We treat separately the case of ideal zero-delay feedback from the BBU, and the hard and soft feedback schemes in the following.

#### A. Ideal Feedback

We first consider for reference the case of zero-delay ideal feedback from the BBU. Since the BBU jointly processes all the received signals for decoding, at the $n$th retransmission, the signal available at the BBU can be written, using (1), as $y^n = [y_1^T, \ldots, y_n^T]^T$, where

$$y_n = \sqrt{\frac{S}{m_t}} H_n x_n + w_n,$$

with $H_n = [h_{1,n}^T, h_{2,n}^T, \ldots, h_{L,n}^T]^T$ and $w_n = [w_{1,n}^T, w_{2,n}^T, \ldots, w_{L,n}^T]^T$. We emphasize that we denoted here $h_{l,n}$ instead of $H_{l,n}$ the vector containing the channel coefficients between the UE and $l$th RRH in the $n$th retransmission, so as to stress the focus on single-antenna RRHs. The effective received signal is hence given by

$$y^n = \sqrt{\frac{S}{m_t}} H_n [x_1^T \cdots x_n^T]^T + [w_1^T \cdots w_n^T]^T.$$
with $\mathcal{H}_n = \text{diag}([\mathbf{H}_1, ..., \mathbf{H}_n])$. Therefore, the decoding error probability at the $n$th transmission is given by $P_e(r, k, \mathcal{H}_n)$.

The C-RAN performance in terms of throughput and the probability of success under ideal feedback can be obtained following the discussion in Sec. [IV] by computing the probability $P(\text{RTX}_n)$ that a retransmission is required at the $n$th transmission attempt. This can be bounded similar to [32] as $P(\text{RTX}_n) \leq P(\hat{D}_n) = E[P_e(r, k, \mathcal{H}_n)]$.

B. Hard Feedback Scheme

With the hard feedback low-latency scheme described in Sec. [III-B], each RRH calculates its own decoding error probability $P_e(r, k, \mathcal{H}_{l,n})$ with $\mathcal{H}_{l,n} = \text{diag}(\mathbf{h}_{l,1}, \mathbf{h}_{l,2}, ..., \mathbf{h}_{l,n})$ and uses the rule [3], which reduces to

$$P_e(r, k, \mathcal{H}_{l,n}) \overset{\text{ACK}}{\leq} P_{\text{th}}.$$  

(40)

Each RRH sends a single bit indicating the ACK/NAK feedback to the UE. The UE decides that a retransmission is necessary as long as all the RRHs return a NAK message, and it stops retransmission otherwise.

Throughput and probability of success can be computed as detailed in Sec. [IV] by using the following probabilities

$$P(\text{D}_n|\text{STOP}_n) = 1$$

$$- E \left[ P_e(r, k, \mathcal{H}_n) \left( \prod_{l=1}^{L} \mathbf{1} \left( P_e(r, k, \mathcal{H}_{l,n}) > P_{\text{th}} \right) \right) = 0 \right]$$

(41)

and

$$P(\text{RTX}_n) = P \left( \prod_{l=1}^{L} \mathbf{1} \left( P_e(r, k, \mathcal{H}_{l,n}) > P_{\text{th}} \right) = 1 \right).$$

(42)

The above probabilities can be calculated similar to the equations derived in Sec. [V] by averaging over the distribution of the eigenvalues of the involved channel matrices.

C. Soft Feedback Scheme

With the soft feedback introduced in Sec. [III-B], each RRH quantizes the local CSI $\mathbf{h}_{l,n}$ with $b$ bits. From the $b$ feedback bits received from each RRH, the UE obtains the quantized channel vectors $\hat{\mathbf{h}}_{l,n}$ for $l \in \{1, ..., L\}$. Based of these, the decision [4] is adopted, which reduces to

$$P_e(r, k, \hat{\mathbf{H}}_n) \overset{\text{STOP}}{\leq} P_{\text{th}},$$

(43)

where $\hat{\mathbf{H}}_n = \text{diag}(\hat{\mathbf{h}}_{1,n}, ..., \hat{\mathbf{h}}_{n,n})$ and $\mathbf{H}_n = [\mathbf{h}_{1,n}^T, ..., \mathbf{h}_{L,n}^T]^T$ collect the quantized CSI. Accordingly, we can compute the desired probabilities as

$$P(\text{D}_n|\text{STOP}_n) = 1 - E[P_e(r, k, \mathcal{H}_n) | P_e(r, k, \hat{\mathbf{H}}_n) \leq P_{\text{th}}]$$

(44)

and

$$P(\text{RTX}_n) = P(\text{P}e(r, k, \hat{\mathbf{H}}_n) > P_{\text{th}}).$$

(45)

The above probabilities can be computed analytically or via Monte Carlo simulations by averaging over the distribution of the eigenvalues similar to Sec. [V].

VII. NUMERICAL RESULTS AND DISCUSSION

In this section, we validate the analysis presented in the previous sections and provide insights on the performance comparison of ideal and local feedback schemes for BBU Hoteling and C-RAN systems via numerical examples.

A. BBU Hoteling

We first study the optimization of the threshold $P_{\text{th}}$ used in the local feedback schemes. As an exemplifying case study, we consider the case of BBU Hoteling described in Sec. [V].

In Fig. 6 and Fig. 7, respectively, the throughput $T$ and the probability of success $P_s$ are shown versus $P_{\text{th}}$ for $s = 3$ dB, $n_{\text{max}} = 5$ retransmissions, $r = 2$ bit/symbol and blocklength $k = 50$ for a SISO link, i.e., for $m_t = 1$ and $m_r = 1$. 

---

Fig. 6. Throughput versus threshold $P_{\text{th}}$ for ideal feedback and local feedback in a BBU Hoteling system ($s = 3$ dB, $n_{\text{max}} = 5$, $r = 2$ bit/symbol, $k = 50$, $m_t = 1$ and $m_r = 1$).

Fig. 7. Probability of success versus threshold $P_{\text{th}}$ in a BBU Hoteling system ($s = 3$ dB, $n_{\text{max}} = 5$, $r = 2$ bit/symbol, $k = 50$, $m_t = 1$ and $m_r = 1$).
The curves have been computed using both the equations derived in Sec. V and Monte Carlo simulations. The latter refer to the simulation of the HARQ process in which the probability of error at the BBU is modeled by means of the Gaussian approximation. The analytical results are confirmed to match with the Monte Carlo simulations, except for the ideal feedback performance of HARQ-CC and HARQ-IR, for which, as discussed in Sec. V, the expressions (27) and (33) yield lower bounds on throughput and probability of success. As seen in the figures, the bounds are very accurate for $k$ as small as 50.

From Fig. 8 and Fig. 9 it is also concluded that throughput and probability of success are maximized for different values of threshold $P_{th}$, with the throughput metric requiring a larger threshold. In fact, a larger value of $P_{th}$, while possibly causing the acknowledgement of packets that will be incorrectly decoded at the BBU, may enhance the throughput by allowing for the transmission of fresh information in a new HARQ session. This is particularly evident for HARQ-TI, for which setting $P_{th} = 1$ guarantees a throughput equal to the case of ideal feedback, but at the cost of a loss in the probability of success. It is also observed that more powerful HARQ schemes such as CC and IR are more robust to a suboptimal choice of $P_{th}$ in terms of throughput, although lower values of $P_{th}$ are necessary in order to enhance the probability of success by avoiding a premature transmission of an ACK message.

We now illustrate in Fig. 8 the throughput loss of local feedback as compared to the ideal feedback case, as a function of the blocklength $k$, for two rates $r = 1$ bit/symbol and $r = 3$ bit/symbol for HARQ-CC and HARQ-IR in a BBU Hoteling system. Henceforth, to avoid clutter in the figures, we only show Monte Carlo results, given the match with analysis discussed above. The simulation are performed by setting $s = 4$ dB, $n_{max} = 10$ and we focus on a SISO link. For every value of $k$, the threshold $P_{th}$ is optimized to maximize the throughput $T$ under the constraint that the probability of success satisfies the requirement $P_s > 0.99$ (see, e.g., [17] and [25]). It can be seen that, as the blocklength increases, the performance loss of local feedback decreases significantly. This reflects a fundamental insight: The performance loss of local feedback is due to the fact that the local decisions are taken by the RRH based only on channel state information, without reference to the specific channel noise realization that affects the received packet. Therefore, as the blocklength $k$ increases, and hence as the errors due to atypical channel noise realizations become less likely, the local decisions tend to be consistent with the actual decoding outcomes at the BBU. In other words, as the blocklength $k$ grows larger, it becomes easier for the RRH to predict the decoding outcome at the BBU: In the Shannon regime of infinite $k$, successful or unsuccessful decoding depends deterministically on whether the rate $r$ is above or below capacity.

A related conclusion can be reached from Fig. 9 where we investigate the throughput for MIMO ($m_t = m_r = m$), MISO ($m_t = m$ and $m_r = 1$) and SIMO ($m_t = 1$ and $m_r = m$) links versus the number of antennas $m$ for HARQ-IR, with $s = 1$ dB, $n_{max} = 10$, $r = 5$ bit/symbol, $k = 100$. As in Fig. 8, the threshold $P_{th}$ is optimized here, and henceforth, to maximize the throughput under the constraint $P_s > 0.99$. As $m$ grows large, it is seen that the throughput of SIMO and MIMO increases up to the maximum throughput $T = r = 5$ bit/symbol. This is unlike the case with MISO, since an increase in the number of transmit antennas only enhances the diversity order but does not improve the average received SNR, yielding a ceiling on the achievable throughput that is smaller than the maximum throughput $T = 5$ bit/symbol.

We remark that the interest in large values of $m$ stems from massive MIMO systems. We also note that the flattening of the throughput for SIMO around $T = 2.5$ bit/symbol for $m$ between 6 and around 20 antennas is due to the fact that, for the given range of $m$, at least two retransmissions are necessary, which implies a throughput equal to $T = r/2 = 2.5$
bit/symbol (see also Fig. 10 for related discussion). As for the throughput loss caused by local feedback, we observe that it is generally minor, ranging from at most 0.27 bit/symbol for MIMO to at most 0.73 bit/symbol for MISO.

B. C-RAN

We now turn our attention to the performance of low-latency local feedback for HARQ-IR over C-RAN systems with \( L > 1 \) single-antenna RRHs and \( m_t = 4 \) antennas at the UE. Throughout, we consider the throughput of local feedback based on hard or soft feedback, under the constraint \( P_s > 0.99 \) on the probability of success. As a reference, we also consider the performance of a BBU Hoteling system, i.e., with \( L = 1 \), under both ideal and local feedback (we mark the latter as “hard feedback” following the discussion in Sec. VII-B).

For soft feedback, we set different values for the number of feedback bits \( b \), including \( b = \infty \), with the latter being equivalent to a BBU Hoteling system with three co-located antennas at the RRH (i.e., \( m_{r,1} = 3 \) and \( L = 1 \)). We use a vector quantizer for each RRH \( l \), in which \( b' \leq b \) bits are used to quantize the channel direction \( \mathbf{h}_{l,n} \) and \( b - b' \) bits for the amplitude \( ||\mathbf{h}_{l,n}|| \). For vector quantization, we generate randomly quantization codebooks with normalized columns (see, e.g., [13]) until finding one for which the constraint on the probability of success is met. The amplitude \( ||\mathbf{h}_{l,n}|| \) of each channel vector is quantized with the remaining \( b' - b \) using a quantizer with numerically optimized thresholds. For \( b = 3, b = 6, b = 9 \) and \( b = 16 \), the number of bits used for the quantization of the direction of each channel vector are \( b' = 1 \), \( b' = 4 \), \( b' = 5 \) and \( b' = 12 \).

In Fig. 10 the throughput of the schemes outlined above is shown versus the SNR parameter \( s \). We first observe that hard feedback, which only require 1 bit of feedback per RRH, is able to improve over the performance of BBU Hoteling, but the throughput is limited by the errors due to the user-centric local decisions based on partial feedback from the RRHs. This limitation is partly overcome by implementing the soft feedback scheme, whose throughput increases for a growing feedback rate. Note that, even with an infinite feedback rate, the performance of local feedback still exhibits a gap as compared to ideal feedback for the same reasons discussed above for BBU Hoteling systems. Also, the flattening of the throughput of less performing schemes around \( T = 2.5 \) for intermediate SNR levels is due to the need to carry out at least two retransmissions unless the SNR is sufficiently large (see, e.g., [26]).

We finally show in Fig. 11 the throughput of ideal and soft feedback schemes versus the blocklength \( k \) for a C-RAN system with \( L = 2 \) and \( L = 3 \). We observe that, in a C-RAN system with a sufficiently small feedback rate such as \( b = 3 \) and \( b = 6 \), an increase in the blocklength \( k \) does not significantly increase the throughput, which is limited by the CSI quantization error. However, with a larger \( b \), such as \( b = 16 \), the throughput can be more significantly improved towards the performance of ideal feedback, especially for a smaller number of RRHs.

VIII. CONCLUDING REMARKS

The performance of BBU Hoteling and C-RAN systems is currently under close scrutiny as limitations due to constraints imposed by fronthaul capacity and latency are increasingly brought to light (see, e.g., [3]). An important enabling technology to bridge the gap between the desired lower cost and higher spectral efficiency of BBU Hoteling and C-RAN and its potentially poor performance in terms of throughput at higher layers is the recently proposed control and data separation architecture [13]. In this context, this work has considered BBU Hoteling and C-RAN systems in which retransmission decisions are made at the edge of the network, that is, by the RRHs or UEs, while data decoding is carried out in a centralized fashion at the BBUs.
As shown, for BBU Hoteling, this class of solutions has the potential to yield throughput values close to those achievable with ideal zero-delay feedback from the BBUs, particularly when the packet is sufficiently long or the number of received antennas is large enough. For C-RAN, it was argued that multibit feedback messages from the RRHs are called for in order to reduce the throughput loss and a specific scheme based on vector quantization was proposed to this end.

Interesting future work include the analysis of control and data separation architectures for C-RAN systems for the purpose of user detection activity in random access in scenarios with a massive number of devices.

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