Control-Data Separation across Edge and Cloud for Uplink Communications in C-RAN

Jinkyu Kang, Osvaldo Simeone, Joonhyuk Kang and Shlomo Shamai (Shitz)

Abstract

Fronthaul limitations in terms of capacity and latency motivate the growing interest in the wireless industry for the study of alternative functional splits between cloud and edge nodes in Cloud Radio Access Network (C-RAN). This work contributes to this line of work by investigating the optimal functional split of control and data plane functionalities at the edge nodes and at the Remote Cloud Center (RCC) as a function of the fronthaul latency. The model under study consists of a two-user time-varying uplink channel in which the RCC has global but delayed channel state information (CSI) due to fronthaul latency, while edge nodes have local but timely CSI. Adopting the adaptive sum-rate as the performance criterion, functional splits whereby the control functionality of rate selection and the decoding of the data-plane frames are carried out at either the edge nodes or at the RCC are compared through analysis and numerical results.

Index Terms

Cloud-Radio Access Network (C-RAN), fronthaul, control data separation, capacity region, Markov processes.

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I. INTRODUCTION

The evolution of the Cloud Radio Access Network (C-RAN) architecture, as traced from its origin [1] to more recent studies [2], points to a shift from fully centralized baseband processing and control to a more balanced functional split between cloud and edge. In particular, while the basic C-RAN system prescribes the implementation of all functions, excluding possibly analog-to-digital and digital-to-analog conversion, at a cloud processor, more recent proposals enable a flexible number of functionalities to be carried out at the edge nodes. This shift is dictated by the realization that a fully centralized C-RAN system entails significant, and possibly prohibitive, requirements on the fronthaul connections between edge nodes and cloud, see, e.g., [3], [4] and references therein.

The demarcation line between the functionalities to be implemented at the cloud and at the edge is typically drawn to include a given number of physical-layer functions at the edge nodes, such as synchronization, FFT/IFFT and resource demapping [3]. The line of work concerned with edge-cloud functional splits generally aims at assessing the trade-off between performance and fronthaul capacity overhead of different demarcation lines. In contrast, references [5]–[7] explore the application of the data-control separation architecture [8] as the guiding principle behind the separation of functionalities between edge and cloud with the aim of addressing fronthaul latency limitations. Specifically, [5] puts forth the idea of performing the control decisions of the uplink hybrid automatic repeat request (HARQ) protocol at an edge node, while keeping the computationally expensive operation of data decoding at the cloud processor. As shown in [6], [7], this approach can yield significant reductions in transmission latency thanks to the capability of the edge nodes to provide quick feedback to the mobile users with limited fronthaul overhead.

An important lesson learned from [5]–[7] is that the implementation of some control functionalities at the edge can be an enabler for the reduction of transmission latency even in the presence of significant delays on the fronthaul links. A work that provides related insights in the different set-up of a multi-hop network with orthogonal links is [9]. Reference [9] shows that centralized scheduling based on delayed
channel state information (CSI) can be outperformed by local scheduling decisions, when each network node has more current CSI about its incoming and outgoing links with respect to the centralized scheduler. Another related idea is put forth in [10], in which part of the scheduling decisions for a wireless downlink channel is carried out at the users by designing the CSI information to be fed back to the base stations.

In this work, we study the optimal functional split of control and data plane functionalities at the edge nodes and cloud for uplink communication. We specifically focus on the following functionalities: (i) the control plane functionality of the data rate selection, and (ii) the data plane functionality of data decoding. We aim at assessing the impact of fronthaul latency on the relative performance of different splits, whereby rate selection and data decoding may be performed separately at either cloud or edge.

The model under study consists of a two-user time-varying uplink channel in which the RCC has global but delayed CSI due to fronthaul latency, while the edge nodes have local but timely CSI. Adopting the adaptive sum-rate as the performance criterion (see, e.g., [11]), different functional splits based on the control-data separation architecture are compared through analysis and numerical results.

The rest of the paper is organized as follows. We describe the system model and performance metric in Sec. II. We analyze different control-data functional splits between RCC and RRSs in Sec. III for a simplified binary Markov channel model and in Sec. IV we address a more general channel model with an arbitrary number of states. In Sec. V, numerical results are presented. Concluding remarks are summarized in Sec. VI.

II. SYSTEM MODEL AND PERFORMANCE METRIC

We consider the uplink of a C-RAN illustrated in Fig. I, which consists of $K$ access points, referred to as remote radio systems (RRSs), a remote cloud center (RCC), and $K$ active user equipments (UEs). Note that we use the nomenclature of [2] to emphasize that the RRSs may be endowed with more processing capabilities than a standard RRH in a C-RAN system. We focus here on the scenario with $K = 2$ in order to simplify the arguments, but the analysis could be generalized to larger systems (see Remark 4). Each UE $i$ is assigned to a RRS, which is identified as RRS $i$. 


Fig. 1. Uplink of the considered C-RAN system.

**System Model:** With the aim of highlighting the impact of interference on the optimal functional split between RRSs and RCC, we model the uplink channels as illustrated in Fig. 1. The signal to noise ratio (SNR) between an UE $i$ and RRS $i$ is denoted as $S$, and is assumed to be constant over $T$ transmission intervals, while the SNR between an UE $j$ and the RRS $i \neq j$ is denoted as $I_i(t)$, and is assumed to vary across the time index $t = 1, 2, \ldots, T$, which runs over the transmission intervals. Note that the assumption of a constant SNR between UE $i$ and RRS $i$ can be in practice justified in the presence of power control at the UE. The more general scenario with time-varying direct channels is studied in Sec. IV.

Furthermore, we assume an ergodic phase fading channel with each transmission interval (see, e.g., [12]), so that the channel matrix between the UEs and the RRSs at any channel use $k$ of the transmission interval $t = 1, 2, \ldots, T$ can be written as

$$
H(t, k) = \begin{bmatrix}
\sqrt{S}e^{j\theta_{11}(t,k)} & \sqrt{I_1(t)}e^{j\theta_{12}(t,k)} \\
\sqrt{I_2(t)}e^{j\theta_{21}(t,k)} & \sqrt{S}e^{j\theta_{22}(t,k)}
\end{bmatrix},
$$

(1)

where the phases $\theta_{ij}(t, k)$ are uniformly distributed in the interval $[0, 2\pi]$, mutually independent, and vary in an ergodic manner over the channel use index $k$ within each transmission interval $t$.

Each RRS $i$ is connected to the RCC via a fronthaul link with a delay of $d$ transmission intervals. As an example, fronthaul transport latency is reported to be around 0.25 ms in [13] for single-hop fronthaul links and can amount to multiple milliseconds in the presence of multihop fronthauling, while fronthaul-related processing at the RCC can take fractions to a few milliseconds [14]. As a result, for transmission intervals
Fig. 2. Markov model for the cross-channel processes $I_i(t)$ and $I_j(t)$ (see Fig. [1]).

of, say 0.5–1 ms, $d$ can be as large as 3–5. Due to the fronthaul delay $d$, the RCC has global but delayed
CSI, namely $I_i(t - d)$ for $i \in \{1, 2\}$. In contrast, each RRS $i$ at time $t$ has local but instantaneous CSI
about the cross-channel $I_i(t)$. This information can be obtained, e.g., by means of uplink training in a
Time Division Duplex system.

For tractability, we assume at first that the SNR $I_i(t)$ on the cross-channel between UE $j$ and RRS $i$
with $i \neq j$ is in two states, namely $I_L$ and $I_H$ with $I_H \geq I_L$. Moreover, the time-varying interference state
is governed by the Markov Chain in Fig. [2] with transition probabilities $p = \Pr[I_i(t + 1) = I_H | I_i(t) = I_L]$ and $q = \Pr[I_i(t + 1) = I_L | I_i(t) = I_H]$. The channels $I_i(t)$ for $i = 1, 2$ are mutually independent. Based on
the definitions above, the probability that the interference state $y$ changes the state $x$ for $x, y \in \{I_L, I_H\}$
after $d$ transmission intervals can be written as

$$\Pr[I_i(t) = x | I_i(t - d) = y] = \beta^{x|y}(d),$$

(2)

where the probability $\beta^{x|y}(d)$ is obtained as the $(x, y)$ entry of the matrix $T^d$, with

$$T = \begin{bmatrix}
1 - p & p \\
q & 1 - q
\end{bmatrix}$$

(3)

being the transition matrix of the Markov chain in Fig. [2]. Moreover, the stationary probabilities for the
“low” and “high” states are obtained as

$$\pi_L = \frac{q}{p + q} \quad \text{and} \quad \pi_H = \frac{p}{p + q},$$

(4)
respectively. A memory parameter $\mu$ can be also defined as $\mu \triangleq 1 - p - q$ and is the second eigenvalue of the transition matrix $T$. Accordingly, $\mu = 1$ represents a static interference process and $\mu = 0$ represents an i.i.d. interference process. The memory parameter $\mu$ can be related to the coherence time of the channel (see Sec. [V]). A more general Markovian model for the cross-channels, as well as for the direct channels, is studied in Sec. [IV]

**RCC-RRS Functional Splits:** Our focus is on the optimization of the functional split between RCC and RRSs, that is, between cloud and edge. Specifically, we will consider different control-data functional splits between the RCC and the RRSs by focusing on the control functionality of rate adaptation, that is, the selection of the transmission rates $R_1$ and $R_2$ (bit/s/Hz) of the two UEs, and on the data plane functionality of data decoding. Specifically, we consider three different control-data functional splits, as described below.

- **Decentralized control-decentralized data** (DC-DD): The DC-DD functional split amounts to the most conventional cellular implementation in which control and data plane functionalities are carried out at the RRSs, that is, at the edge. Based on the available current CSI, each RRS $i$ individually selects the transmission rate $R_i$ for user $i$, hence performing decentralized control. Moreover, each RRS $i$ individually performs decentralized local data decoding of the signal transmitted by user $i$.

- **Centralized control-centralized data** (CC-CD): The CC-CD functional split corresponds to the standard C-RAN implementation in which the RCC carries out both control and data processing. Specifically, based on the available delayed CSI, the RCC selects the transmission rates $R_1$ and $R_2$ for the users, hence performing centralized control. Moreover, upon reception of the signals received by the RRSs on the fronthaul links, the RCC performs centralized joint data decoding.

- **Decentralized control-centralized data** (DC-CD): In this hybrid implementation, based on the available current CSI, each RRS $i$ individually allocates the rate $R_i$ for user $i$, hence performing decentralized control. The RCC instead performs centralized joint data decoding based on the signals received on the fronthaul links.
Performance Metric: To compare different functional splits, we will use the performance metric of the adaptive sum-rate (with no power control) used in [11] and references therein. This is defined as the average sum-rate that can be achieved while guaranteeing no outage in each transmission slot, where the average is taken here with respect to the steady-state distribution (4) of the random channel gains \( \{I_1(t), I_2(t)\} \). To be more precise, in each transmission interval, transmission rates \( R_1 \) for user 1 and \( R_2 \) for user 2 are chosen by the RCC or by the RRSs, depending on the functional splits, so that no outage occurs. The adaptive sum-rate is the average of the sum rates \( R_1 + R_2 \). We will also consider, as discussed below, a generalized metric, termed adaptive outage sum-rate, in which a (small) outage probability \( \epsilon \) is allowed, where an outage event is caused by the imperfect knowledge of the CSI.

III. Analysis of the Control-Data Functional Splits

In this section, we analyze the performance in terms of the adaptive sum-rates of the mentioned control-data functional splits between RCC and RRSs in the presence of the fronthaul transmission delay \( d \). Throughout, we define \( C_{xy} \) as

\[
C_{xy} \triangleq \mathbb{E}[\log_2 \det(I + H_{xy}H_{xy}^\dagger)],
\]

for \( x, y \in \{L, H\} \), where \( H_{xy} = [\sqrt{S}e^{j\theta_11} \sqrt{I_x}e^{j\theta_12}; \sqrt{I_y}e^{j\theta_21} \sqrt{S}e^{j\theta_22}] \) and the expectation is taken over the random phases \( \theta = [\theta_{11}, \theta_{12}, \theta_{21}, \theta_{22}] \) which are mutually independent and uniformly distributed in the interval \([0, 2\pi]\). Note that this is the maximum achievable sum-rate in a time-slot with \( I_1(t) = I_x \) and \( I_2(t) = I_y \) if joint data decoding is performed at the RCC (see, e.g., [15, Ch. 4]). We will also use the notation \( C_{I_1I_2} \) for \( C_{xy} \) when \( I_1 = I_x \) and \( I_2 = I_y \). We also observe that \( C_{LH} = C_{HL} \).

A. Decentralized Control - Decentralized Data (DC-DD)

Here, we study the conventional cellular implementation based on DC-DD. Accordingly, each RRS \( i \) selects the transmission rate \( R_i \) for the user \( i \) in its cell based on the available current CSI \( I_i(t) \) and performs local data decoding. We further assume the standard approach of treating interference from the out-of-cell user as noise for local decoding.
Based on the mentioned assumptions, the rate for each user can be adapted at each RRS based on the CSI $I_i(t) = I_x$ by choosing the transmission rate $R_i = R_x \triangleq \log_2(1 + S/(1 + I_x))$. This choice guarantees no outage. The resulting maximum adaptive sum-rate $R_{DC-DD}$ is summarized in the following lemma. Note that this rate does not depend on the fronthaul delay $d$, which does not affect the performance of DC-DD.

**Lemma 1:** With DC-DD, the maximum adaptive sum-rate is given by

$$R_{DC-DD} = 2\pi L R_L + 2\pi L \pi H (R_L + R_H) + 2\pi H R_H. \quad (6)$$

**Remark 1:** If one alleviated the constraint of zero outage, the adaptive rate could be raised to $R_H$ by choosing $R_1 = R_2 = R_H$ irrespective of the CSI but at the cost of accepting an outage probability equal to $1 - \pi_H^2$, which is generally high and hence of little interest\(^1\).

**B. Decentralized Control - Centralized Data (DC-CD)**

With DC-CD, the transmission rate $R_i$ for user $i$ is selected by each RRS $i$ based on the available current CSI $I_i(t)$ as for DC-DD, while the RCC performs centralized joint data decoding on behalf of the RRSs. The set of achievable rate pairs $(R_1, R_2)$ with joint decoding at the RCC is given by the capacity region $C_{I_1(t)I_2(t)}$ of the ergodic multiple access channel between the two users at the two RRSs. Using standard results in network information theory (see, e.g., [15, Ch. 4]), we have

$$C_{I_1(t)I_2(t)} = \begin{cases} 
(R_1, R_2) & R_1 \leq \log_2(1 + S + I_2(t)) \\
& R_2 \leq \log_2(1 + S + I_1(t)) \\
& R_1 + R_2 \leq C_{I_1(t)I_2(t)} 
\end{cases}. \quad (7)$$

The capacity regions $C_{LL}, C_{LH}, C_{HL}, C_{HH}$ are illustrated in Fig. 3. We note that, in case $C_{LL} \leq C_{LL}/2 + \log_2(1 + S + I_L)$, there are rate pairs that are achievable rates that maximize the sum-rate in both capacity regions $C_{LL}$ and $C_{HL}$, the points marked as b and c in Fig. 3(a), while this is not true for case $C_{LL} > C_{LL}/2 + \log_2(1 + S + I_L)$ as can be seen in Fig. 3(b) and Fig. 3(c).\(^1\)

\(^1\)One could also consider setting $R_1 = R_H$ and $R_2$ selected on the basis of $I_2$ but the outage probability would again be generally too large to be interesting.
Fig. 3. Capacity regions $C_{xy}$ in (7) when the interference realizations are $I_1 = I_x$ and $I_2 = I_y$ if (a) $C_{LH} \leq C_{LL}/2 + \log_2(1 + S + I_L)$; (b) $C_{LL}/2 + \log_2(1 + S + I_L) < C_{LH} \leq 2 \log_2(1 + S + I_L)$; and (c) $2 \log_2(1 + S + I_L) < C_{LH}$. The points a, b, c, and d indicate the four rate pairs $(R_x, R_y)$ selected by the DC-CD scheme in Sec. III-B and the points A, B, C, D, E, and E' denote the rates selected by the RCC in the CC-CD scheme discussed in Sec. III-C.
We define as $R_L$ and $R_H$ the rates selected by each RRS $i$ when $I_i(t) = I_L$ and $I_i(t) = I_H$, respectively. The outage probability is the probability that the rate pair $(R_{I_i(t)}, R_{I_2(t)})$ does not belong to the capacity region $C_{I_i(t) I_2(t)}$. The next proposition provides the maximum adaptive sum-rate for DC-CD based on an optimized choice of the rates $R_L$ and $R_H$. Specifically, it shows that the optimal rate pairs $(R_L, R_L), (R_L, R_H), (R_H, R_L)$ and $(R_H, R_H)$ are given by the points a, b, c and d, respectively, in Fig. 3.

**Proposition 1:** With DC-CD, the maximum adaptive sum-rate $R^{DC-CD}$ is given as

$$R^{DC-CD} = 2\pi^2 R_L + 2\pi L\pi H (R_L + R_H) + 2\pi^2 H R_H,$$

where $R_L$ is given as

$$R_L = \begin{cases} 
C_{LL}/2 & \text{if } C_{LH} > C_{LL}/2 + \log_2(1 + S + I_L), \\
C_{LL}/2 & \text{if } C_{LH} \leq C_{LL}/2 + \log_2(1 + S + I_L) \text{ and } \pi_L^2 > \pi_H^2, \\
C_{LH} - \log_2(1 + S + I_L) & \text{if } C_{LH} \leq C_{LL}/2 + \log_2(1 + S + I_L) \text{ and } \pi_L^2 \leq \pi_H^2,
\end{cases}$$

and $R_H$ is given as

$$R_H = \begin{cases} 
\log_2(1 + S + I_L) & \text{if } C_{LH} > C_{LL}/2 + \log_2(1 + S + I_L), \\
C_{LH} - C_{LL}/2 & \text{if } C_{LH} \leq C_{LL}/2 + \log_2(1 + S + I_L) \text{ and } \pi_L^2 > \pi_H^2, \\
\log_2(1 + S + I_L) & \text{if } C_{LH} \leq C_{LL}/2 + \log_2(1 + S + I_L) \text{ and } \pi_L^2 \leq \pi_H^2.
\end{cases}$$

**Proof:** In order to guarantee no outage, the rate pair $(R_L, R_L)$ must be inside the capacity region $C_{LL}$, and hence, from Fig. 3 the rate $R_L$ should be selected in the interval $[0, C_{LL}/2]$. In a similar manner, the rate pair $(R_L, R_H)$ (or $(R_H, R_L)$) should be inside the capacity region $C_{LH}$ (or $C_{HL}$). Therefore, the rate $R_H$ can be no larger than $\min(C_{LH} - R_L, \log_2(1 + S + I_L))$. Finally, the rate pair $(R_H, R_H)$ must belong to the capacity region $C_{HH}$, which is guaranteed by the conditions derived above. Based on these considerations, the adaptive sum-rate can be computed by solving the problem

$$\begin{align*}
\text{maximize} & \quad 2(\pi_L^2 + \pi_L \pi_H) R_L + 2(\pi_L \pi_H + \pi_H^2) \min(C_{LH} - R_L, \log_2(1 + S + I_L)) \\
\text{s.t.} & \quad 0 \leq R_L \leq C_{LL}/2,
\end{align*}$$

where the objective is obtained by averaging the achievable rate as in (20). Solving the linear max-min program [16] yields (9).
**Remark 2:** In a manner similar to the discussion in Remark 1 for DC-DD, by allowing for a non-zero outage probability, one could increase the sum-rate achievable with DC-CD. Nevertheless, the probability of success, i.e., the complement of the outage probability, would be of the order of the steady-state probability $\pi_H$ which may be too small to make this option of practical interest.

**C. Centralized Control - Centralized Data (CC-CD)**

With the C-RAN mode of CC-CD processing, at any transmission interval $t$, the RCC performs rate adaptation in a centralized manner based on the available delayed CSI, namely $\{I_1(t-d), I_2(t-d)\}$. Furthermore, the RCC performs centralized joint data decoding on behalf of the connected RRSs. Due to joint decoding, an outage occurs at time $t$ if the rate pair $(R_{1,xy}, R_{2,xy})$ selected by the RCC when the delayed CSI is $I_1(t-d) = I_x$ and $I_2(t-d) = I_y$ is outside the capacity region $C_{I_1(t)I_2(t)}$ in (7). Accordingly, the outage probability $P_{xy}^{out}$ in a time slot $t$ for which the CSI available at the scheduler is $I_1(t-d) = I_x$ and $I_2(t-d) = I_y$ can be computed as

$$P_{xy}^{out} = \Pr [(R_{1,xy}, R_{2,xy}) \notin C_{I_1(t)I_2(t)} | I_1(t-d) = I_x, I_2(t-d) = I_y] .$$

(12)

For reference, we first observe the case of no fronthaul delay, i.e., $d = 0$, the RCC has perfect CSI $I_i(t)$ for all $i \in \{1,2\}$. Therefore, the RCC can adapt the transmission rates to the current CSI to achieve the maximum sum-rate $C_{I_1(t)I_2(t)}$ due to joint decoding at the RCC. The resulting adaptive sum-rate is given as

$$R_{d=0}^{CC\text{-}CD} = \pi_L^2 C_{LL} + 2\pi_L \pi_H C_{LH} + \pi_H^2 C_{HH} .$$

(13)

This follows since, when $I_1(t) = I_x$ and $I_2(t) = I_y$, the RCC can select the rates $R_{1,xy}$ and $R_{2,xy}$ such that the selected rates are inside the capacity region $C_{xy}$ and $R_{1,xy} + R_{2,xy} = C_{xy}$ (see Fig. 3).

In contrast to the case with no fronthaul delay, if the fronthaul link has delay $d$, the RCC has delayed CSI, namely $\{I_1(t-d), I_2(t-d)\}$, and is hence not informed about the current capacity region $C_{I_1(t)I_2(t)}$ in (7). An outage event can thus be generally avoided only if transmitting always at the minimum sum-rate
$C_{LL}$, since the latter yields rate pairs that are within the capacity region in all other states (see Fig. 3). Therefore, with $d > 0$, the adaptive sum-rate of CC-CD is given by $R^{CC-CD}_d = C_{LL}$.

Based on the discussion above, CC-CD is outperformed by DC-CD when $d > 0$ in terms of adaptive sum-rate. To enable additional insights into the performance of CC-CD, we then consider a generalized performance metric, termed adaptive outage sum-rate, that allows for an outage probability (12) no larger than $\epsilon$. We note that this definition is sensible for CC-CD since outage event can occur in this case due to the, typically small, uncertainty about the CSI at the RCC in the practical case when $d$ is not large. This is not the case with DC in which each RRS has no CSI about the cross-channel relative to the other RRS (see Remark 1 and Remark 2). To formulate the resulting adaptive outage sum-rate, we define the probabilities $P^{HH}_{xy} = \beta^H|x(d)\beta^H|y(d)$, $P^{LH}_{xy} = \beta^L|x(d)\beta^H|y(d)$, $P^{HL}_{xy} = \beta^H|x(d)\beta^L|y(d)$, and $P^{LL}_{xy} = \beta^L|x(d)\beta^L|y(d)$, where the notation $P^{x'y'}_{xy}$ indicates the probability of transitioning from delayed states $\{I_1(t-d) = I_x, I_2(t-d) = I_y\}$ to current states $\{I_1(t) = I_{x'}, I_2(t) = I_{y'}\}$. The next proposition provides an achievable outage adaptive sum-rate.

Proposition 2: With CC-CD, the outage adaptive sum-rate $R^{CC-CD}_d(\epsilon)$ is achievable with outage probability $\epsilon$, where

$$R^{CC-CD}_d(\epsilon) = \pi^2 L R_{LL} + 2\pi L \pi H R_{LH} + \pi^2 H R_{HH}, \quad (14)$$

with $R_{xy}$ being defined as

$$R_{xy} = \begin{cases} 
C_{LL} & \text{if } \epsilon \leq P^{LL}_{xy}, \\
C_{LH} & \text{if } P^{LL}_{xy} < \epsilon \leq 1 - P^{HH}_{xy}, \\
C_{HH} & \text{if } 1 - P^{HH}_{xy} < \epsilon \leq 1, \end{cases} \quad (15)$$

if $C_{LH} \leq 2 \log_2(1 + S + I_L)$, and as

$$R_{xy} = \begin{cases} 
C_{LL} & \text{if } \epsilon \leq P^{LL}_{xy}, \\
2 \log_2(1 + S + I_L) & \text{if } P^{LL}_{xy} < \epsilon \leq \tilde{P}_{xy}, \\
C_{LH} & \text{if } \tilde{P}_{xy} < \epsilon \leq 1 - P^{HH}_{xy}, \\
C_{HH} & \text{if } 1 - P^{HH}_{xy} < \epsilon \leq 1, \end{cases} \quad (16)$$
if \( C_{ LH } > 2 \log_2(1 + S + I_L) \), with \( \tilde{P}_{xy} = \min( P_{xy}^{LH}, P_{xy}^{HL}) + P_{xy}^{LL} \).

**Proof:** See Appendix A for the proof.

**Remark 3:** With zero fronthaul delay, i.e., \( d = 0 \), the adaptive outage sum-rate \( R_{CC-CD}^d(\epsilon) \) in (14) with \( \epsilon = 0 \) coincides with the adaptive sum-rate (13). For \( d > 0 \), it is at present not known if (14) is the maximum outage adaptive sum-rate.

**IV. TIME-VARYING DIRECT AND CROSS CHANNELS**

We now consider the more general case in which both the direct channel \( S_i(t) \) and cross-channel \( I_i(t) \) processes are time-varying and are described by independent Markov chains with an arbitrary finite number of states.

**A. System Model**

The system model is the same as described in Sec. II with the caveat that both the SNR between an UE \( i \) and RRS \( i \), which is denoted as \( S_i(t) \), and the SNR between an UE \( j \) and the RRS \( i \neq j \), which is denoted as \( I_i(t) \), are assumed to vary across the transmission intervals \( t = 1, 2, \ldots, T \). Specifically, we assume that the direct channel \( S_i(t) \) can take \( N_S \) values, indexed in ascending order as \( \{S_1, \ldots, S_{N_S}\} \), and is governed by a Markov chain with transition probabilities \( p_{S,mn} = \Pr[S_i(t+1) = S_m|S_i(t) = S_n] \). In a similar manner, the interference channel \( I_i(t) \) can take \( N_I \) values, indexed in ascending order as \( \{I_1, \ldots, I_{N_I}\} \), and varies according to a Markov chain with transition probabilities \( p_{I,mn} = \Pr[I_i(t+1) = I_m|I_i(t) = I_n] \). We recall that Markovian models are extensively adopted for the evaluation of the performance of wireless systems (see, e.g., [17]–[19]).

According to the adopted Markov model, the probability that the direct channel state changes from state \( S_n \) to the state \( S_m \), for \( m, n \in \{1, \ldots, N_S\} \), after \( d \) transmission intervals can be written as

\[
\Pr[S_i(t) = S_m|S_i(t-d) = S_n] = \beta_{S,m|n}(d),
\]

where the probability \( \beta_{S,m|n}(d) \) is obtained as the \( (m,n) \) entry of the matrix \( T_S^d \), with the transition matrix \( T_S \) having \( p_{S,mn} \) as the \( (m,n) \) entry, i.e., \( [T_S]_{m,n} = p_{S,mn} \). Moreover, the stationary probability for the
state $S_m$ is obtained by solving the linear system as (see, e.g., [20])

$$
\pi_{S,m} = \sum_{n \in \mathcal{S}} \pi_{S,n} p_{S,mn},
$$

for $m \in \{1, \ldots, N_S\}$. Analogously, we define $\beta_{I}^{m,n}(d)$ as the $d$-step transition probability for the interference process, with $m, n \in \{1, \ldots, N_I\}$, and $\pi_{I,m}$ as the steady-state probability of the interference process.

An ergodic phase fading channel model is adopted as in (1) with $S_i(t)$, for $i = 1, 2$, to be substituted for $S$. Accordingly, we define the rate $C_{mn,xy}$ as

$$
C_{mn,xy} \triangleq \mathbb{E}[\log_2 \det(I + H_{mn,xy} H_{mn,xy}^\dagger)],
$$

for $m, n \in \{1, \ldots, N_S\}$ and $x, y \in \{1, \ldots, N_I\}$, where we have introduced the channel matrix $H_{mn,xy} = [\sqrt{S_m} e^{j\theta_{11}} \sqrt{T_x} e^{j\theta_{12}}; \sqrt{T_y} e^{j\theta_{21}} \sqrt{S_n} e^{j\theta_{22}}]$ and the expectation is taken over the random phases $\theta = [\theta_{11}, \theta_{12}, \theta_{21}, \theta_{22}]$, which are mutually independent and uniformly distributed in the interval $[0, 2\pi]$. Note that this is the maximum achievable sum-rate in a time-slot with channel gains $S_1(t) = S_m$, $S_2(t) = S_n$, $I_1(t) = I_x$, and $I_2(t) = I_y$ if joint data decoding is performed at the RCC (see, e.g., [15, Ch. 4]). We will also use the notation $C_{S_1S_2I_1I_2}$ for $C_{mn,xy}$ when $S_1 = S_m$, $S_2 = S_n$, $I_1 = I_x$, and $I_2 = I_y$.

As in Sec. [II] the RCC has global but delayed CSI about the direct channel $S_i(t - d)$ and cross-channel $I_i(t - d)$ for $i \in \{1, 2\}$. In contrast, each RRS $i$ at time $t$ has local but instantaneous CSI, namely it is aware only of $S_i(t)$ and $I_i(t)$.

### B. Decentralized Control - Decentralized Data (DC-DD)

With DC-DD, the transmission rate $R_i = R_{m,x}$ for the user $i$ is selected by each RRS $i$ based on the available current direct channel $S_i(t) = S_m$ and cross-channel $I_i(t) = I_x$, so as to guarantee no outage when decoding is performed by treating interference as noise at the RRS $i$. The resulting rate is given as $R_i = R_{m,x} \triangleq \log_2(1 + S_m/(1 + I_x))$, for $m \in \{1, \ldots, N_S\}$ and $x \in \{1, \ldots, N_I\}$. The corresponding maximum adaptive sum-rate can be expressed in terms of the steady-state probabilities of the channel processes and is summarized in the following lemma.
Lemma 2: With DC-DD, the maximum adaptive sum-rate is given by

\[ R_{DC-DD} = \sum_{m,n=1}^{N_S} \sum_{x,y=1}^{N_I} \pi_{S,m} \pi_{S,n} \pi_{I,x} \pi_{I,y} (R_{m,x} + R_{n,y}). \] (20)

C. Decentralized Control - Centralized Data (DC-CD)

With DC-CD, the transmission rate \( R_i \) for user \( i \) is selected by each RRS \( i \) based on the available current CSI \( S_i(t) \) and \( I_i(t) \) as for DC-DD, while the RCC performs centralized joint data decoding on behalf of the RRSs. The set of achievable rate pairs \((R_1, R_2)\) with joint decoding at the RCC when the channel states are \((S_1(t), S_2(t), I_1(t), I_2(t))\) is given by the capacity region \( C_{S_1(t)S_2(t),I_1(t)I_2(t)} \) of the ergodic multiple access channel between the two users at the two RRSs. Using standard results in network information theory (see, e.g., [15, Ch. 4]), we have

\[ C_{S_1(t)S_2(t),I_1(t)I_2(t)} = \begin{cases} R_1 \leq \log_2 (1 + S_1(t) + I_2(t)) \\ R_2 \leq \log_2 (1 + S_2(t) + I_1(t)) \\ R_1 + R_2 \leq C_{S_1(t)S_2(t),I_1(t)I_2(t)} \end{cases} \] (21)

We define as \( R_{m,x} \) the rate selected by each RRS \( i \) when the available channel set \((S_i(t) = S_m, I_i(t) = I_x)\) for \( m \in \{1, \ldots, N_S\} \) and \( x \in \{1, \ldots, N_I\} \). When \( S_i(t) = S_m, S_2(t) = S_n, I_1(t) = I_x, \) and \( I_2(t) = I_y \), the outage probability is the probability that the rate pair \((R_{m,x}, R_{n,y})\) does not belong to the capacity region \( C_{S_1(t)S_2(t),I_1(t)I_2(t)} \). The problem of maximizing the adaptive sum-rate over the choice of the rates \( \{R_{m,x}\} \) for \( m \in \{1, \ldots, N_S\} \) and \( x \in \{1, \ldots, N_I\} \), under the constraint of no outage (see Fig. 3) can be written as

\[
\begin{align*}
\text{maximize} & \quad \sum_{m,n=1}^{N_S} \sum_{x,y=1}^{N_I} \pi_{S,m} \pi_{S,n} \pi_{I,x} \pi_{I,y} (R_{m,x} + R_{n,y}) \\
\text{s.t.} & \quad (R_{m,x}, R_{n,y}) \in C_{S_mS_n,I_xI_y},
\end{align*}
\] (22a)

where the constraint (22b) applies to \( m, n \in \{1, \ldots, N_S\} \) and \( x, y \in \{1, \ldots, N_I\} \). The problem (22) is a linear program (LP) and can be tackled using standard solvers.
D. Centralized Control - Centralized Data (CC-CD)

With CC-CD, the transmission rates $R_1 = R_{1,mn,xy}$, $R_2 = R_{2,mn,xy}$ are selected by the RCC based on the available delayed CSI \( \{S_1(t-d) = m, S_2(t-d) = n, I_1(t-d) = x, I_2(t-d) = y\} \) and joint data decoding is performed at the RCC. Therefore, an outage occurs at time $t$ if the selected rate pair $(R_1, R_2)$ is outside the capacity region $C_{S_1(t)S_2(t),I_1(t)I_2(t)}$. Accordingly, following the discussion in Sec. [III-C], with a fronthaul delay $d > 0$, in order to avoid an outage event, the adaptive sum-rate of CC-CD is given by the minimum sum-rate $R_{d}^{CC-CD} = C_{11,11}$.

As in Sec. [III-C] we now analyze the performance of CC-CD in terms of the adaptive outage sum-rate in which the outage probability no larger than $\epsilon$ is allowed. To this end, we define an outage sum-rate region $C_{mn,xy}^{e}$ as the set of rate pairs $(R_1, R_2)$ such that the probability that $(R_1, R_2)$ does not belong to the capacity region $C_{S_1(t)S_2(t),I_1(t)I_2(t)}$ when $S_1(t-d) = S_m$, $S_2(t-d) = S_n$, $I_1(t-d) = I_x$, and $I_2(t-d) = I_y$ is smaller than $\epsilon$. As a result of this definition, choosing a rate pair in $C_{mn,xy}^{e}$ when $S_1(t-d) = S_m$, $S_2(t-d) = S_n$, $I_1(t-d) = I_x$, and $I_2(t-d) = I_y$ guarantees a probability of outage smaller than or equal to $\epsilon$. To obtain one such region, we define as $\bar{S}_{m}^{e}$ the $\epsilon$-percentile of the conditional distribution $\beta_{S_m}^{im}(d)$, that is, the maximum value $x \in \{S_1, \ldots, S_{N_S}\}$ such that $\Pr[S_i(t) \leq x | S_i(t-d) = S_m] \leq \epsilon$. We similarly define as $\bar{I}_{m}^{e}$ the $\epsilon$-percentile of the conditional distribution $\beta_{I_m}^{im}(d)$. A rate region $C_{mn,xy}^{e}$ with the desired property in terms of outage probability can hence be defined as

\[
C_{mn,xy}^{e} = \begin{cases} 
(R_1, R_2) & R_1 \leq \log_2(1 + \bar{S}_m^{e/4} + \bar{I}_y^{e/4}) \\
 & R_2 \leq \log_2(1 + \bar{S}_n^{e/4} + \bar{I}_x^{e/4}) \\
 & R_1 + R_2 \leq C_{S_m^{e/4},S_n^{e/4},I_x^{e/4},I_y^{e/4}}^{e/4} 
\end{cases}
\]  \hfill (23)

Note that we have used the fact that the probability that a rate pair in $C_{mn,xy}^{e}$ does not belong to $C_{S_1(t)S_2(t),I_1(t)I_2(t)}$ when $S_1(t-d) = S_m$, $S_2(t-d) = S_n$, $I_1(t-d) = I_x$, and $I_2(t-d) = I_y$ can be upper bounded by the union bound as

\[
\Pr[S_1(t) \leq \bar{S}_m^{e/4}] + \Pr[S_2(t) \leq \bar{S}_n^{e/4}] + \Pr[I_1(t) \leq \bar{I}_x^{e/4}] + \Pr[I_2(t) \leq \bar{I}_y^{e/4}] \leq \epsilon,
\]  \hfill (24)

by construction. The problem of maximizing the resulting achievable adaptive outage sum-rate over the
choice of the sum-rates \( \{ R_{mn,xy} \} \) for \( m, n \in \{1, \ldots, N_S \} \) and \( x, y \in \{1, \ldots, N_I \} \) under the constraint of outage upper bounded by \( \epsilon \) can be then formulated as

\[
\begin{align*}
\text{maximize} & \quad \sum_{m,n=1}^{N_S} \sum_{x,y=1}^{N_I} \pi_{S,m} \pi_{S,n} \pi_{I,x} \pi_{I,y} R_{mn,xy} \\
\text{s.t.} & \quad R_{mn,xy} \in C_{mn,xy},
\end{align*}
\]  

(25a)

(25b)

where the constraint (25b) applies to \( m, n \in \{1, \ldots, N_S \} \) and \( x, y \in \{1, \ldots, N_I \} \). As for problem (22), this is an LP and can be solved using standard tools.

Remark 4: The formulation in this sections can be extended to a more general scenario including \( M \) RRSs and \( M \) UEs with \( M > 2 \). This does not require any new concept since the arguments used to analyze the three functional splits directly extend to this more general set-up at the only cost of a more cumbersome notation. For instance, the optimization problems formulated for CC-DC and CC-CD can be stated in terms of the steady-state probabilities and the capacity region of an ergodic multiple access channel with \( M \) receiving antennas and \( M \) UEs.

V. NUMERICAL RESULTS

In this section, we evaluate the performance of the considered splits of control and data functions between cloud and edge in terms of the adaptive (outage) sum-rate as a function of key system parameters such as fronthaul delay and channel variability. We start by considering the case studied in Sec. III in which the direct channels are fixed, due to power control, while the cross-channels vary according to the two-state Markov chain in Fig. 2. Under this model, in Fig. 4 and Fig. 5, we set the SNR of the desired signal as \( SNR = S/N_0 = 0 \text{ dB} \) with noise power \( N_0 = 1 \); and we assume that the SIR is \( SIR_H = S/I_H = -10 \text{ dB} \) when the cross-channel is in the high state \( I_H \), while it equals \( SIR_L = S/I_L = 0 \text{ dB} \) when the cross-channel is in the low state \( I_L \). Moreover, we parameterize the transition probabilities \( p \) and \( q \) as \( p = q = (1 - \mu)/2 \), with \( \mu \) being the memory parameter discussed in Sec. II.

For the mentioned conditions, Fig. 4 shows the adaptive sum-rate as function of the fronthaul delay \( d \) when the memory parameter is \( \mu = 0.9 \). With this choice, the average coherence time is \( 1/p = 1/q = 20 \)
transmission intervals. For reference, under Clarke’s model, when the carrier frequency is $c/\lambda = 1$ GHz, where $c = 3 \times 10^8$ m/s and $\lambda$ is the wavelength, and the transmission interval is 0.5 ms, using the approximate expression for the coherence time $0.423 \lambda/v$ [21], this corresponds to a velocity $v \approx 46$ km/h. From the figure, we first observe that, as expected, the centralized data decoding performed by DC-CD strictly improves over the decentralized decoding of DC-DD, irrespective of the fronthaul delay $d$, which does not affect the performance of either scheme. In contrast, the centralized control carried out by CC-CD is only able to enhance the sum-rate when the fronthaul latency is sufficiently small and the system allows for a non-zero outage. For example, for an outage level $\epsilon = 0.05$, CC-CD improves over DC-CD only as long as the fronthaul latency is no larger than two transmission intervals, i.e., $d < 2$. In this regard, from Remark 1 and Remark 2 we observe that, since $\pi_H = 1/2$, an outage probability of $\epsilon = 0.05$ does not allow to increase the sum-rate for either DC-DD or DC-CD.

The impact of the memory parameter $\mu$ is studied in Fig. 5, where the adaptive sum-rate is plotted versus $\mu$ with a fronthaul delay $d = 1$. We only show the range $\mu > 0.5$ since, for $\mu < 0.5$, the sum-rates
Fig. 5. Adaptive sum-rate vs. memory parameter $\mu$ under two-state Markov model for the cross-channels ($N_S = N_I = 2$, $SNR = 0$ dB, $SIR_H = -10$ dB, $SIR_L = 0$ dB, $d = 1$ and $p = q = (1 - \mu)/2$).

The sum-rates do not change significantly as compared to $\mu = 0.5$. We note that, for Clarke’s model with the parameters discussed above, the range $[0.5, 1]$ for $\mu$ corresponds approximately to interval of velocities $[0, 230]$ (km/h).

In keeping with the discussion above, CC-CD is seen to outperform DC-CD for $\mu$ sufficiently large. For example, with $\epsilon = 0.1$ at $\mu = 0.9$, CC-CD provides a rate gain over the decentralized schemes. Overall, this discussion points to a conclusion that is in line with the main result in [9] for the problem of scheduling in a multi-hop network (see Sec. I): *Centralized control based on global but delayed CSI can yield a degraded performance as compared to decentralized control based on local but timely CSI.*

We now turn to consider the more general case studied in Sec. IV in which both direct channel and cross-channel vary according to Markov chains with $N_S = N_I > 2$ states. Specifically, we adopt the equal-probability method proposed in [17] to approximate Clarke’s model with a finite-state Markov chain, as shown in Fig. 6. Accordingly, channel variations can only occur between adjacent states, i.e., $p_{x,mn} = 0$ if $|m - n| > 1$ for $x \in \{S, I\}$. Furthermore, defining as $\gamma_S$ the average SNR of the direct channel states, the values $\{S_1, \ldots, S_{N_S}\}$ of the direct channel gains are obtained by selecting $S_m$ to be equal to...
the middle point in the quantization interval \([\Gamma_{x,m}, \Gamma_{x,m+1})\), which is identified by solving the equations \(1/N_x = \exp(-\Gamma_{x,m}/\gamma_x) - \exp(-\Gamma_{x,m+1}/\gamma_x)\) with \(\Gamma_{x,1} = 0\) and \(\Gamma_{x,N_x+1} = \infty\) for \(m = 1, \ldots, N_x\). In a similar manner, defining as \(\gamma_I\) the average SNR of the cross-channel states, the value \(I_m\) is equal to the middle point in each quantization interval \([\Gamma_{I,m}, \Gamma_{I,m+1})\), which is obtained by solving the equation \(1/N_I = \exp(-\Gamma_{I,m}/\gamma_I) - \exp(-\Gamma_{I,m+1}/\gamma_I)\) with \(\Gamma_{I,1} = 0\) and \(\Gamma_{I,N_I+1} = \infty\) for \(m = 1, \ldots, N_I\). Finally, the transition probabilities are defined as

\[
p_{x,mn} = \begin{cases} 
\frac{N(\Gamma_{x,m}) T_p}{\pi_{x,n}} & \text{if } m = n + 1, \\
\frac{N(\Gamma_{x,n}) T_p}{\pi_{x,n}} & \text{if } m = n - 1, \\
0 & \text{if } |m - n| > 1,
\end{cases}
\]

(26)

for \(x \in \{S, I\}\), where \(N(\Gamma_{x,m}) = \sqrt{2\pi\Gamma_{x,m}/\gamma_x}v/\lambda \exp(\Gamma_{x,m}/\gamma_x)\) is the crossing rate of state \(\Gamma_{x,m}\) for the direct or cross-channel processes [17] and \(T_p\) is the transmission interval. Here, we set the carrier frequency to \(c/\lambda = 1\) GHz and the transmission interval \(T_p = 0.5\) ms.

For this set-up, in Fig. 7, the adaptive sum-rate is plotted versus the fronthaul delay with \(N_S = N_I = 6\), \(\gamma_S = -5\) dB, \(\gamma_I = 5\) dB, and \(v = 46\) km/h, as in Fig. 4. The qualitative behavior observed in Fig. 7 is confirmed, although CC-CD is shown to outperform the other functional splits in a large interval of delays due to the slower channel variability that is accounted for by the model in Fig. 6 as compared to two-state Markov model with a similar velocity. The effect of mobile velocity \(v\) is further investigated in Fig. 8 with the same parameters and \(d = 3\). It is observed that CC-CD is advantageous in the regime of low mobile velocity due to large channel coherence interval (cf. Fig. 5).

In order to obtain further insight into the operating requires in which different functional splits are to
Fig. 7. Adaptive sum-rate vs. fronthaul delay $d$ under the finite-state Markov model [17] for both signal and interference processes ($N_S = N_I = 6$, $\gamma_S = -5$ dB, $\gamma_I = 5$ dB, and $v = 46$ km/h).

Fig. 8. Adaptive sum-rate vs. mobile velocity $v$ under the finite-state Markov model [17] for both signal and interference processes ($N_S = N_I = 6$, $\gamma_S = -5$ dB, $\gamma_I = 5$ dB, and $d = 3$).
Fig. 9. Regions of the plane \((d, v)\) in which DC-CD or CC-CD yield a larger adaptive sum-rate when allowing an outage of \(\epsilon = 0\) (region \(\textcircled{1}\)) and \(\epsilon = 0.1\) (region \(\textcircled{2}\)) under the finite-state Markov model [17] for both signal and interference processes \((N_S = N_I = 6, \gamma_S = -5 \text{ dB}, \text{ and } \gamma_I = 5 \text{ dB})\).

be preferred. Fig. 9 shows the regions of the plane with coordinates given by the fronthaul delay \(d\) and mobile velocity \(v\) in which each scheme offers the best adaptive sum-rate. The DC-CD scheme is seen to be advantageous in the area above the uppermost solid line, while CC-CD with \(\epsilon \leq 0.1\) is to be preferred in the complementary regime below this line. In particular, in the region \(\textcircled{1}\) CC-CD outperforms DC-CD, and hence also DC-DD, even when allowing for no outage, while in the region \(\textcircled{2}\) CC-CD outperforms DC-CD for \(\epsilon = 0.1\). The uppermost boundary lines for each region hence provide the maximum fronthaul delay \(d\) that can be tolerated by the CC-CD scheme for a given value of \(v\) while still yielding gains as compared to DC-CD scheme when \(\epsilon = 0\) or \(\epsilon = 0.1\).

VI. CONCLUSIONS

The control-data separation architecture offers a promising guiding principle for the implementation of functional splits between edge and cloud in C-RAN systems that are limited by the fronthaul latency. In this paper, we have analyzed the relative merits of alternative functional splits whereby rate selection
and data decoding are carried out either at the edge or at the cloud by adopting the analytically tractable criterion of adaptive sum-rate. Our results show that the fully centralized architecture favored in the original instantiation of the C-RAN architecture is to be preferred only if the fronthaul latency is small or the time-variability of the channel is limited. Otherwise, moving the control functionality of rate selection at the edge while performing joint data decoding at the cloud yields potentially significant gains. This conclusion demonstrates the value of decentralized but timely CSI as compared to centralized but delayed CSI for the purpose of scheduling.

Among interesting open problems, we mention here the study of models that allow for a more general definition of functional splits including a flexible demarcation line at the physical layer. Another interesting open aspect is the impact of outage events due to quasi-static fading, both in terms of coding strategies at the physical layer such as the broadcast approach [22] and of retransmission policies at the data link layer. Finally, it would be interesting to study downlink communication under the same assumptions on the heterogeneity of CSI available at edge and cloud considered in this paper.

APPENDIX A

The RCC chooses the rates $R_{1,xy}$ and $R_{2,xy}$ when $I_1(t-d) = I_x$ and $I_2(t-d) = I_y$ in such a way that the probability that the chosen rates are outside the capacity region $C_{I_1(t)I_2(t)}$ for the current channel states $I_1(t)$ and $I_2(t)$ in (7) is less than $\epsilon$. Specifically, referring to Fig. [3] for an illustration, when $I_1(t-d) = I_x$ and $I_2(t-d) = I_y$:

- If $\epsilon \leq P_{xy}^{LL}$, the RCC selects $R_{1,xy} = R_{2,xy} = C_{LL}/2$ (point A in Fig. [3]);
- If $1 - P_{xy}^{HH} < \epsilon \leq 1$, the RCC selects $R_{1,xy} = R_{2,xy} = C_{HH}/2$ (point B in Fig. [3]);
- If $P_{xy}^{LL} < \epsilon \leq 1 - P_{xy}^{HH}$ and $C_{LH} \leq 2 \log_2(1+S+I_L)$, the RCC selects $R_{1,xy} = R_{2,xy} = C_{LH}/2$ (point C in Fig. [3(a)] and Fig. [3(b)]);  
- If $P_{xy}^{LL} < \epsilon \leq \bar{P}_{xy}$ and $C_{LH} > 2 \log_2(1+S+I_L)$, the RCC selects $R_{1,xy} = R_{2,xy} = \log_2(1+S+I_L)$ (point D in Fig. [3(c)]);
• If $\bar{P}_{xy} < \epsilon \leq 1 - P_{xy}^{HH}$ and $C_{LL} > 2 \log_2(1 + S + I_L)$, the RCC selects either $R_{1,xy} = C_{LL} - \log_2(1 + S + I_L)$ and $R_{2,xy} = \log_2(1 + S + I_L)$ (point E' in Fig. 3(c)), or $R_{1,xy} = \log_2(1 + S + I_L)$ and $R_{2,xy} = C_{LL} - \log_2(1 + S + I_L)$ (point E'' in Fig. 3(e)), where the first rate pair is selected when $P_{xy}^{HL} + P_{xy}^{LL} < P_{xy}^{HL} + P_{xy}^{LL}$ and the other pair otherwise.

We will argue next that these choices guarantee a probability of outage (12) no larger than $\epsilon$.

A. When $R_{1,xy} + R_{2,xy} = C_{LL}$ (point A in Fig. 3), the probability of outage can be easily seen to be zero, as discussed before, because the capacity region $C_{LL}$ is included in a capacity region $C_{I_1(t)I_2(t)}$ with any current channel states $\{I_1(t), I_2(t)\}$.

B. If the rates are selected so that $R_{1,xy} + R_{2,xy} = C_{HH}$ (point B in Fig. 3), the upper bound (12) on the outage probability is easily seen to be $1 - P_{xy}^{HH}$, which, in the relevant regime, does not exceed $\epsilon$, since any interference state other than $I_1(t) = I_H$ and $I_2(t) = I_H$ causes an outage. It can also be noted that the upper bound (12) is in fact tight, since the outage events for the two users coincide.

C. If $C_{LL} \leq 2 \log_2(1 + S + I_L)$, the capacity regions (7) are shown in Fig. 3(a) and Fig. 3(b). If the rates are selected to be $R_{1,xy} = R_{2,xy} = C_{LL}/2$ (point C in Fig. 3(a) and Fig. 3(b)), the upper bound on the probability of outage can be calculated as $P_{xy}^{LL}$, since only the interference state $\{I_1(t) = I_L, I_2(t) = I_L\}$ causes an outage. Again, this probability is, by definition of the scheduling scheme, less than $\epsilon$, and the upper bound is in fact tight.

D. If $C_{LL} > 2 \log_2(1 + S + I_L)$, the capacity regions (7) are shown in Fig. 3(c). If the rates are selected such that $R_{1,xy} = R_{2,xy} = \log_2(1 + S + I_L)$ (point D in Fig. 3(e)), the upper bound (12) on the outage probability is easily seen to be tight and equal to $P_{xy}^{LL}$, which is smaller than $\epsilon$ in the relevant regime.

E. If $C_{LL} > 2 \log_2(1 + S + I_L)$ and the rate pair $(R_{1,xy}, R_{2,xy}) = (C_{LL} - \log_2(1 + S + I_L), \log_2(1 + S + I_L))$ at E' is selected, the upper bound (12) on the probability of outage is equal to $P_{xy}^{HL} + P_{xy}^{LL}$ and tight. This is because an outage for both users is caused by the states $(I_1(t), I_2(t)) = (I_H, I_L)$ and $(I_1(t), I_2(t)) = (I_L, I_L)$. In a similar manner, if the rate pair $(R_{1,xy}, R_{2,xy}) = (\log_2(1 + S + I_L), C_{LL} - \log_2(1 + S + I_L))$ at E'' is selected, the probability of outage is given as $P_{xy}^{HL} + P_{xy}^{LL}$. Therefore, by selecting between
the rate pairs at $E'$ and $E''$, we obtain the probability of outage \( \tilde{P}_{xy} = \min(P_{xy}^{HL} + P_{xy}^{LL}, P_{xy}^{LH} + P_{xy}^{LL}) \). This outage probability is also smaller than \( \epsilon \) by construction of the scheduling scheme.

**References**

[1] J. Huang and R. Duan, “C-RAN: the road towards green RAN,” White Paper, ver. 3.0, China mobile Research Institute, Oct. 2013.

[2] J. Huang and Y. Yuan, “White paper of next generation fronthaul interface,” [Online]. Available: labs.chinamobile.com/cran, ver. 1.0, China mobile Research Institute, Jun. 2015.

[3] D. Wubben, P. Rost, J. Bartelt, M. Lalam, V. Savin, M. Gorgoglione, A. Dekorsy, and G. Fettweis, “Benefits and impact of cloud computing on 5G signal processing: Flexible centralization through cloud-RAN,” *IEEE Sig. Proc. Mag.*, vol. 31, no. 6, pp. 35–44, Nov. 2014.

[4] O. Simeone, A. Maeder, M. Peng, O. Sahin, and W. Yu, “Cloud radio access network: Virtualizing wireless access for dense heterogeneous networks,” to appear in *Journal of Communications and Networks*, 2016.

[5] U. Dotsch, M. Doll, H. P. Mayer, F. Schaich, J. Segel, and P. Sehier, “Quantitative analysis of split base station processing and determination of advantageous architectures for LTE,” *Bell Labs Technical Journal*, vol. 18, no. 1, pp. 105–128, Jun. 2013.

[6] P. Rost and A. Prasad, “Opportunistic hybrid ARQ: Enabler of centralized-RAN over nonideal backhaul,” *IEEE Wireless Comm. Lett.*, vol. 3, no. 5, pp. 481–484, Jul. 2014.

[7] S. Khalili and O. Simeone, “Inter-layer per-mobile optimization of cloud mobile computing: A message passing approach,” *Transactions on Emerging Telecommunication Technologies*, vol. 27, no. 6, pp. 814–827, Feb. 2016.

[8] A. Mohamed, O. Onireti, M. Imran, A. Imran, and R. Tafazolli, “Control-data separation architecture for cellular radio access networks: A survey and outlook,” *IEEE Communications Surveys and Tutorials*, vol. 18, no. 1, pp. 446–465, Jun. 2015.

[9] M. Johnston and E. Modiano, “A new look at wireless scheduling with delayed information,” *Proc. IEEE Int. Symp. Info. Th.*, pp. 1407–1411, Hong Kong, Jun. 2015.

[10] M. Deghel, M. Assaad, and M. Debbah, “Opportunistic feedback reporting and scheduling scheme for multichannel wireless networks,” *Proc. IEEE Glob. Comm. Conf.*, pp. 1–6, Washington, DC USA, Dec. 2016.

[11] S. Sreekumar, B. Dey, and S. Pillai, “Distributed rate adaptation and power control in fading multiple access channels,” *IEEE Trans. Info. Th.*, vol. 61, no. 10, pp. 5504–5524, Oct. 2015.

[12] G. Kramer, M. Gastpar, and P. Gupta, “Cooperative strategies and capacity theorems for relay networks,” *IEEE Trans. Info. Th.*, vol. 51, no. 9, pp. 3037–3063, Sep. 2005.

[13] NGMN Alliance, “Further study on critical C-RAN technologies,” [Online] Available: https://www.ngmn.org, Mar. 2015.

[14] N. Nikaein, “Processing radio access network functions in the cloud: Critical issues and modeling,” in *Proc. of Int. Workshop on Mobile Cloud Computing and Services*, pp. 36–42, Paris, France, Sep. 2015.

[15] A. E. Gamal and Y.-H. Kim, *Network Information Theory*. Cambridge University Press, 2011.
[16] J. E. Falk, “A linear max-min problem,” Math. Program., vol. 5, no. 1, pp. 169–188, 1973.

[17] H. S. Wang and N. Moayeri, “Finite-state Markov channel-a useful model for radio communication channels,” IEEE Trans. on Veh. Technol., vol. 44, no. 1, pp. 163 –171, Feb. 1995.

[18] Y. Wei, F. R. Yu, and M. Song, “Distributed optimal relay selection in wireless cooperative networks with finite-state Markov channels,” IEEE Trans. on Veh. Technol., vol. 59, no. 5, pp. 2149–2158, Feb. 2010.

[19] K. Zheng, F. Liu, L. Lei, C. Lin, and Y. Jiang, “Stochastic performance analysis of a wireless finite-state Markov channel,” IEEE Trans. Wireless Comm., vol. 12, no. 2, pp. 782–793, Jan. 2013.

[20] J. R. Norris, Markov Chains. Cambridge University Press, 1998.

[21] T. S. Rappaport, Wireless Communications: Principles and Practice. Prentice-Hall, 1996.

[22] S. Shamai, “A broadcast approach for the multiple-access slow fading channel,” Proc. IEEE Int. Symp. Info. Th., p. 128, Sorrento, Italy, Jun. 2000.