Robust Uplink Communications over Fading Channels with Variable Backhaul Connectivity

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***Abstract*—Two mobile users communicate with a central decoder via two base stations. Communication between the mobile users and the base stations takes place over a Gaussian interference channel with constant channel gains or quasi-static fading. Instead, the base stations are connected to the central decoder through orthogonal finite-capacity links, whose connectivity is subject to random fluctuations. There is only receive-side channel state information, and hence the mobile users are unaware of the channel state and of the backhaul connectivity state, while the base stations know the fading coefficients but are uncertain about the backhaul links' state. The base stations are oblivious to the mobile users' codebooks and employ compress-and-forward to relay information to the central decoder. Lower bounds on average achievable throughput are obtained by proposing strategies that combine the broadcast coding approach and layered distributed compression techniques. Numerical results confirm the advantages of the proposed approach with respect to conventional non-robust strategies in both scenarios with and without fading.**

I. Introduction

Modern cellular communication systems that implement the idea of network MIMO [1] can be modeled by two-hop channels. Considering the uplink and with reference to Fig. 1, the first hop corresponds to the channels between the Mobile Users (MUs) and the Base Stations (BSs), while the second hop accounts for communication between the BSs and the Remote Central Processor (RCP) that performs decoding across all connected cells. The first hop is generally to be regarded as a fading interference channel, capturing the wireless connection between MUs and BSs. Instead, the second hop can be often modeled by orthogonal wireless or wired backhaul links between each BS and the RCP. A specific implementation of network MIMO that is becoming of increasing interest is the so called cloud radio access network, whereby the BSs act as "soft" relays towards the destination (see, e.g., [2]).

The performance of the uplink system of Fig. 1, and close variants, with compress-and-forward (i.e., "soft") relays has been studied in [3] and [4] assuming non-fading channels in the first hop and backhaul links of given capacity in the second hop. Focusing on a *single-MU system*, ergodic fading channels in the first hop are considered in [5], on-off non-ergodic backhaul links are considered in [6], while the case with quasi-static fading in both the first and the second hop is studied in [7].

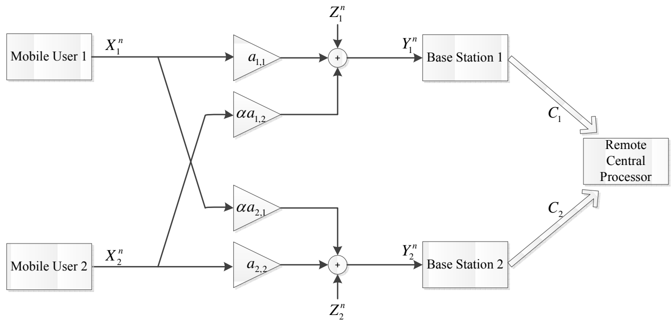

Fig. 1. Two-cell Gaussian cellular uplink channel with variable capacity backhaul links.

In this paper, we revisit the system model in Fig. 1 by assuming *multiple MUs*, both non-fading and quasi-static fading channels for the first hop and backhaul links with non-ergodic variable connectivity. Specifically, the backhaul links are assumed to be in one of two possible states, modeling in a simple fashion either wireless or wired links of variable connectivity conditions. The main focus of this paper, as in [3], [4] and [6], is on applications in which MUs and BSs have to operate with only receive but not transmit channel state information. In particular, the MUs are assumed to be aware neither of the fading channels nor of the backhaul links' state, while the BSs are not informed about the state of the backhaul links. This is the case for instance in low-delay applications in which it is not possible to accommodate feedback to the MUs and BSs. As in [6],[7], the MUs cope with the lack of channel state information by accepting variable-rate data delivery via Broadcast Coding (BC) [8]. Moreover, in order to opportunistically leverage better backhaul conditions, we resort to layered compression at the relays as in [6]. Overall, the proposed approach, detailed in Section III, can be seen as an extension of [6] to a set-up with multiple users, fading channels in the first hop and a more general backhaul state model. Numerical results presented in Section IV demonstrate the effectiveness of the proposed robust strategy with respect to standard non-robust schemes.

II. System Model and Preliminaries

We consider the uplink cellular multiple access model of Fig. 1 that consists of two identical cells, indexed by $j = 1, 2$. Each cell includes a single-antenna MU and a single-antenna

BS. The MUs wish to send information to a RCP, using the BSs as relay stations. The received signals at the BSs for time index i read

$$Y_{1,i} = a_{1,1}X_{1,i} + \alpha a_{1,2}X_{2,i} + Z_{1,i}, \quad (1a)$$

$$Y_{2,i} = \alpha a_{2,1}X_{1,i} + a_{2,2}X_{2,i} + Z_{2,i} \quad (1b)$$

for $i = 1, 2, \ldots, n$, where $(a_{1,1}, a_{1,2}, a_{2,1}, a_{2,2})$ represent the channel gains, $X_{j,i}$ represent the signal transmitted by MU j, $Z_{j,i}$ are Gaussian noises, and the inter-cell interference path loss coefficient is $0 \le \alpha \le 1$. Each jth MU has an average power constraint $\frac{1}{n}\sum_{i=1}^{n} |x_{j,i}|^2 \le P$ for $j = 1, 2$.

Two scenarios will be considered in the paper. The first consists of *non-fading* channels, that is, we have $a_{1,1} = a_{1,2} = a_{2,1} = a_{2,2} = 1$. In this case, it is assumed that the symbols $X_{1,i}$ and $X_{2,i}$ are real and that the noise is distributed as $Z_{j,i} \sim \mathcal{N}(0, 1)$. This assumption is made without loss of generality since the in-phase and quadrature components of the equivalent baseband signal can be treated separately in the absence of fading.

In the second scenario, Rayleigh *quasi-static fading* channels are assumed, and thus the channel coefficients $a_{1,1}, a_{1,2}, a_{2,1}$ and $a_{2,2}$ are independent, distributed as $\mathcal{CN}(0, 1)$, and constant during the transmission block. The transmitted signals $X_{1,i}$ and $X_{2,i}$ are complex and the noise is distributed $Z_{j,i} \sim \mathcal{CN}(0, 1)$.

The BSs are connected to the RCP via orthogonal finite-capacity backhaul links, e.g., dedicated wireless or wired connections. The connectivity of the backhaul links is uncertain in the sense that the capacities C_1 and C_2 of the two links are independent and can have two possible states: a *low-capacity* state, in which the capacity is C, with probability p, and a *high-capacity* state, in which the capacity is $C + \Delta C$ with $\Delta C \ge 0$, with probability $1-p$. Also, the state of the backhaul links remains constant in the communication block.

We assume only receive-side channel state information. As a result, the fading channels are only known at the BSs and at the RCP, while the state of the backhaul links is only known at the RCP.

Following the principle of cloud radio access networks, the BSs are unaware of the codebooks used by the MUs and operate by compressing the baseband received signal. Specifically, the jth BS compresses the received signal Y_j^n to produce the indices $s_j \in \{1, 2, \ldots, 2^{nC}\}$ and $r_j \in \{1, 2, \ldots, 2^{n\Delta C}\}$ that are transmitted through the jth backhaul link. When the jth backhaul link is in the low-capacity state (C), the RCP receives only the s_j index, and, when it is in the high-capacity state ($C + \Delta C$), both indices s_j and r_j are received by the RCP.

In order to combat fading and the uncertainty of the backhaul links, the MUs employ the BC approach [8]. Accordingly, each MU divides its information message M_j into K independent sub-messages $M_j = (M_{j,1}, M_{j,2}, \ldots, M_{j,K})$, $j = 1, 2$. Let $R_{j,k}$ be the rate of the kth message, $k = 1, 2, \ldots, K$, i.e., $M_{j,k} \in \{1, 2, \ldots, 2^{nR_{j,k}}\}$. Moreover, for a given channel-backhaul realization $(\mathbf{a}, \mathbf{c}) \triangleq (a_{1,1}, a_{1,2}, a_{2,1}, a_{2,2}, c_1, c_2)$, where $c_j \in \{C, C + \Delta C\}$, let $\mathcal{I}_{(\mathbf{a},\mathbf{c})}$ be the set of indices of messages that can be decoded by the RCP, that is

$$\mathcal{I}_{(\mathbf{a},\mathbf{c})} = \{\, (j, k) \in \mathcal{A}_{J,K} \,|\, M_{j,k} \text{ is decodable given } (\mathbf{a}, \mathbf{c})\} \quad (2)$$

where $\mathcal{A}_{J,K} \triangleq \{1, 2\} \times \{1, 2, \ldots, K\}$. This set depends on the specific coding/decoding strategy, as it will be discussed. Finally, define the throughput given the channel-backhaul realization $(\mathbf{a}, \mathbf{c})$ as

$$T_{(\mathbf{a},\mathbf{c})} = \sum_{(j,k) \in \mathcal{I}_{(\mathbf{a},\mathbf{c})}} R_{j,k}. \quad (3)$$

The performance criterion of interest is the average achievable throughput T, where the average is taken with respect to the a priori probability of fading coefficients and backhaul link state.

III. Achievable Throughput

A. No Fading

In this section, the special case where there is no fading is considered. Without fading, the only uncertainty of the MUs and BSs is on the state of the backhaul links. In fact, there are four possible states of the backhaul links (C_1, C_2), namely $(C, C), (C + \Delta C, C), (C, C + \Delta C)$ and $(C + \Delta C, C + \Delta C)$, which will be labeled as state 1, state 2, state 3 and state 4, respectively. We denote by "Decoder l" the decoding scheme used by the RCP in state l, $l = 1, 2, 3, 4$. Note that, Decoder 2 might not be able to decode messages that Decoder 3 can decode, and vice versa, since they receive different subsets of indices from the BSs (see Fig. 2). This situation contrasts with the (non-fading) single-user model studied in [6], in which, due to the symmetry of the system model, the states could be ordered depending on their decoding power.

To deal with the backhaul uncertainty, we adopt the broadcast strategy proposed in [9] in the context of broadcasting under delay constraints. Accordingly, both MUs use five messages ($K = 5$): messages $(M_{1,1}, M_{2,1})$ are to be decoded by the RCP no matter what the backhaul state is, and hence by Decoder 1, 2, 3, 4; $(M_{1,2}, M_{2,2})$ are to be decoded when either $C_1 = C + \Delta C$ or $C_2 = C + \Delta C$, and hence by Decoder 2, 3 and 4; $(M_{1,3}, M_{2,4})$ are to be decoded whenever $C_1 = C + \Delta C$, and hence by Decoder 2 and 4; $(M_{1,4}, M_{2,3})$ are to be decoded whenever $C_2 = C + \Delta C$, and hence by Decoder 3 and 4; and $(M_{1,5}, M_{2,5})$ are to be decoded when both $C_1 = C + \Delta C$ and $C_2 = C + \Delta C$, and hence only by Decoder 4. The assignment of messages and decoders is illustrated in Fig. 2. As a result of these choices, (3) can be written as: $T_1 \triangleq T_{(C,C)} = \sum_{j=1}^{2} R_{j,1}$, $T_2 \triangleq T_{(C+\Delta C,C)} = \sum_{j=1}^{2}\sum_{k=1}^{2} R_{j,k} + R_{1,3} + R_{2,4}$, $T_3 \triangleq T_{(C,C+\Delta C)} = \sum_{j=1}^{2}\sum_{k=1}^{2} R_{j,k} + R_{1,4} + R_{2,3}$ and $T_4 \triangleq T_{(C+\Delta C,C+\Delta C)} = \sum_{j=1}^{2}\sum_{k=1}^{5} R_{j,k}$, and the average throughput T is thus

$$T = p^2 T_1 + p(1-p)\,(T_2 + T_3) + (1-p)^2 T_4. \quad (4)$$

Decoding at the RCP is performed as follows. As mentioned, the jth BS sends two indices, s_j and r_j, on the

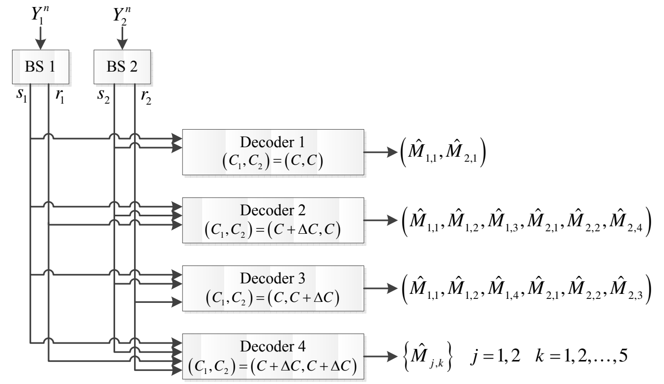

Fig. 2. Illustration of the decoding strategy for the proposed BC scheme for the non-fading model.

backhaul link. These are obtained by compressing the received signal Y_j^n using a layered quantization codebook: the base layer provides a coarse description of Y_j^n and is encoded only in the index s_j, while the overall codebook provides a refined description of Y_j^n and is encoded by both indices (s_j, r_j). The rate of the coarse description is C bits, while the rate of the refined description is $(C + \Delta C)$ bits. The RCP first recovers the compressed versions of the received signals Y_j^n, either coarse or refined, depending on the backhaul links' state. These compressed received signals are used by the RCP to decode the messages corresponding to the current state of the backhaul links, as illustrated in Fig. 2.

The proposed approach achieves the average throughput described in the following proposition.

Proposition 1 (BC and separate decompression)**.** *Let $\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5 \geq 0$ such that $\sum_{l=1}^{5} \lambda_l = 1$. The average throughput* (4) *is achievable with* (5) *at the bottom of the page, where*

$$\mathbf{A}_1 \triangleq \begin{pmatrix} 1 & \alpha \\ \alpha & \alpha^2 \end{pmatrix} \text{ and } \mathbf{A}_2 \triangleq \begin{pmatrix} \alpha^2 & \alpha \\ \alpha & 1 \end{pmatrix}, \tag{6}$$

$$\sigma_1^2 = \frac{2^{2C}\left(2^{2\Delta C}-1\right)\left(P(1+\alpha^2)+1\right)}{\left(2^{2C}-1\right)\left(2^{2(C+\Delta C)}-1\right)}, \tag{7a}$$

$$\sigma_2^2 = \frac{P(1+\alpha^2)+1}{2^{2(C+\Delta C)}-1}, \tag{7b}$$

and for $\mathcal{I}_1, \mathcal{I}_2 \subseteq \{1,2,3,4,5\}$

$$\mathbf{\Lambda}_I\left(\mathcal{I}_1, \mathcal{I}_2\right) \triangleq P\left[\left(\sum_{k\in\mathcal{I}_1} \lambda_k\right)\mathbf{A}_1 + \left(\sum_{k\in\mathcal{I}_2} \lambda_k\right)\mathbf{A}_2\right]. \tag{8}$$

Note that $\mathbf{I}$ denotes the 2×2 identity matrix, $\operatorname{diag}(a, b)$ represents a diagonal matrix with main diagonal (a, b), and $[j]_2 \triangleq j \bmod 2$. Proposition 1 is proved in [10, App. A], and a brief discussion is presented here. The MUs use BC based on i.i.d. generated Gaussian codebooks, where parameters $(\lambda_1, \lambda_2, \ldots, \lambda_5)$ represent the power allocation used by both MUs to transmit the five messages $M_{j,1}, \ldots, M_{j,5}$. Specifically, the transmitted signal can be written as

$$X_j = \sqrt{P}\sum_{k=1}^{5}\sqrt{\lambda_k}W_{j,k}, \tag{9}$$

where $W_{j,k} \sim \mathcal{N}(0, 1)$ for $k = 1, \ldots, 5$, are the independent variables representing the five codebooks used to encode the corresponding messages $M_{j,k}$ for $k = 1, \ldots, 5$. In every backhaul state, the layers $W_{j,k}$ that cannot be decoded by the RCP act as additional additive noise, as in classical BC [8], while all the messages that are to be retrieved according to Fig. 2 are jointly decoded. As a result, matrix $\mathbf{\Lambda}_I(\mathcal{I}_1, \mathcal{I}_2)$ in (8) is the covariance matrix of the interfering signal corresponding to the uncoded messages when the messages $\{M_{j,k}\}$ with $k \in \mathcal{I}_j$ and $j = 1, 2$ cannot be decoded in the current backhaul links state.

The quantities (σ_1^2, σ_2^2) in (7) represent the quantization noise introduced by compression at the BSs. Specifically, the jth BS produces the coarse description $V_{j,1}^n$ and the refined description $V_{j,2}^n$ using the Gaussian test channels $V_{j,1} = Y_j + Q_{j,1} + Q_{j,2}$ and $V_{j,2} = Y_j + Q_{j,2}$, respectively, where $Q_{j,1} \sim \mathcal{N}(0, \sigma_1^2)$ and $Q_{j,2} \sim \mathcal{N}(0, \sigma_2^2)$. As detailed in [10, App. A], the variances σ_1^2 and σ_2^2 are derived by assuming separate decompression of the indices of the two BSs by the RCP. A more efficient compression/decompression strategy can leverage the fact that the signals received by the BSs are correlated. Specifically, we can allow the RCP to jointly decompress the basic descriptions encoded in indices s_1 and s_2 by using distributed source coding, or binning, on the basic descriptions at the BSs. The throughput achieved by this strategy can be found in [10, Proposition 2].

$$R_{1,1} + R_{2,1} < \frac{1}{2}\log\det\left(\mathbf{I} + \lambda_1 P\left(\mathbf{A}_1 + \mathbf{A}_2\right)\left[\mathbf{\Lambda}_I\left(\{2,3,4,5\},\{2,3,4,5\}\right) + \left(1+\sigma_1^2+\sigma_2^2\right)\mathbf{I}\right]^{-1}\right) \tag{5a}$$

$$R_{1,2} + R_{2,2} < \frac{1}{2}\log\det\left(\mathbf{I} + \lambda_2 P\left(\mathbf{A}_1 + \mathbf{A}_2\right)\left[\mathbf{\Lambda}_I\left(\{3,4,5\},\{3,4,5\}\right) + \operatorname{diag}\left(1+\sigma_2^2, 1+\sigma_1^2+\sigma_2^2\right)\right]^{-1}\right), \tag{5b}$$

$$R_{j,3} < \frac{1}{2}\log\det\left(\mathbf{I} + \lambda_3 P\mathbf{A}_1\left[\mathbf{\Lambda}_I\left(\{4,5\},\{3,5\}\right) + \operatorname{diag}\left(1+\sigma_2^2, 1+\sigma_1^2+\sigma_2^2\right)\right]^{-1}\right), \tag{5c}$$

$$R_{j,4} < \frac{1}{2}\log\det\left(\mathbf{I} + \lambda_4 P\mathbf{A}_2\left[\mathbf{\Lambda}_I\left(\{4,5\},\{3,5\}\right) + \operatorname{diag}\left(1+\sigma_2^2, 1+\sigma_1^2+\sigma_2^2\right)\right]^{-1}\right), \tag{5d}$$

$$R_{j,3} + R_{[j]_2+1,4} < \frac{1}{2}\log\det\left(\mathbf{I} + P\left(\lambda_3\mathbf{A}_1 + \lambda_4\mathbf{A}_2\right)\left[\mathbf{\Lambda}_I\left(\{4,5\},\{3,5\}\right) + \operatorname{diag}\left(1+\sigma_2^2, 1+\sigma_1^2+\sigma_2^2\right)\right]^{-1}\right), \tag{5e}$$

$$R_{1,5} + R_{2,5} < \frac{1}{2}\log\det\left(\mathbf{I} + \lambda_5 P\left(1+\sigma_2^2\right)^{-1}\left(\mathbf{A}_1 + \mathbf{A}_2\right)\right), \tag{5f}$$

B. Quasi-Static Fading Channels

In this section we study the scenario with quasi-static fading. While, as discussed in the previous section, the backhaul links have four possible states, the fading channels introduce an uncountable number of possible channel-backhaul states $(\mathbf{a}, \mathbf{c})$. As a result, in principle, BC requires each MU to send an infinite number of layers to cope with the uncertainty on both fading channels and backhaul links (see [8]). However, works such as [11] suggest that the full benefits of BC can be often obtained with a very limited number of layers. Based on these results and aiming at reducing the complexity of the analysis, here we focus on two-layer BC ($K = 2$). Therefore, each MU j decomposes its message in two independent parts as $M_j = (M_{j,1}, M_{j,2})$ with rates $R_{j,k}$, $k = 1, 2$, i.e., $M_{j,k} \in \{1, 2, \ldots, 2^{nR_{j,k}}\}$. Moreover, we consider compression at the BSs based on (complex) Gaussian test channels and successive refinement, similar to what was done for the non-fading case. We recall that the BSs know the fading state and thus can adjust the compression noise variances to the current fading conditions.

Based on the compressed received signals of the BSs recovered at the RCP, the latter attempts decoding of the MUs' messages. Unlike the non-fading case, here the messages to be decoded are not determined by the backhaul state only (cf. Fig. 2), but also by the fading states. In order to assess which subset of messages $(M_{1,1}, M_{1,2}, M_{2,1}, M_{2,2})$ are decodable in state $(\mathbf{a}, \mathbf{c})$, we assume a successive decoding approach in which the RCP first attempts to decode jointly the first-layer messages $(M_{1,1}, M_{2,1})$ and then, if the first-layer messages are both decoded correctly, it jointly decodes the second-layer messages $(M_{1,2}, M_{2,2})$.

Proposition 2 (Common outage decoding). *Let $\lambda_1, \lambda_2 \geq 0$ such that $\lambda_1 + \lambda_2 = 1$. The average throughput*

$$T = \Pr\{\mathcal{R}_1\}(R_{1,1} + R_{2,1}) + \Pr\{\mathcal{R}_1 \cap \mathcal{R}_2\}(R_{1,2} + R_{2,2}) \quad (10)$$

is achievable, where the sets $\mathcal{R}_1$ and $\mathcal{R}_2$ are defined as (11) for $j = 1, 2$, at the bottom of the page,

$$\mathbf{A}_1 \triangleq \begin{pmatrix} |a_{1,1}|^2 & \alpha a_{1,1} a_{2,1}^* \\ \alpha a_{1,1}^* a_{2,1} & \alpha^2 |a_{2,1}|^2 \end{pmatrix}, \quad (12a)$$

$$\mathbf{A}_2 \triangleq \begin{pmatrix} \alpha^2 |a_{1,2}|^2 & \alpha a_{1,2} a_{2,2}^* \\ \alpha a_{1,2}^* a_{2,2} & |a_{2,2}|^2 \end{pmatrix}, \quad (12b)$$

and for $j = 1, 2$

$$f_j(C_j) = \begin{cases} 1 + \sigma_{j,1}^2 + \sigma_{j,2}^2 & C_j = C \\ 1 + \sigma_{j,2}^2 & C_j = C + \Delta C \end{cases} \quad (13)$$

with

$$\sigma_{j,1}^2 = \frac{2^C\left(2^{\Delta C} - 1\right)\left(P\left(|a_{j,j}|^2 + \alpha^2 \left|a_{j,[j]_2+1}\right|^2\right) + 1\right)}{\left(2^C - 1\right)\left(2^{C+\Delta C} - 1\right)}, \quad (14a)$$

$$\sigma_{j,2}^2 = \frac{P\left(|a_{j,j}|^2 + \alpha^2 \left|a_{j,[j]_2+1}\right|^2\right) + 1}{2^{C+\Delta C} - 1}. \quad (14b)$$

Note that $\mathbb{1}_{\{j=1\}}$ equals 1 for $j = 1$ and 0 otherwise. Proposition 2 is proved in [10, App. B]. The random throughput takes on two values, namely $R_{1,1} + R_{2,1}$ with probability $\Pr\{\mathcal{R}_1 \cap \mathcal{R}_2^C\}$, and $R_{1,1} + R_{1,2} + R_{2,1} + R_{2,2}$ with probability $\Pr\{\mathcal{R}_1 \cap \mathcal{R}_2\}$. Set $\mathcal{R}_1$ represents the subset of channel-backhaul states $(\mathbf{a}, \mathbf{c})$ in which the first-layer messages of both MUs are jointly decodable. Similarly, the set $\mathcal{R}_2$ is the subset of channel-backhaul states $(\mathbf{a}, \mathbf{c})$ for which the second-layer messages of the MUs are decodable when conditioning on the event that both first-layer messages have been decoded correctly.

In the strategy used by Proposition 2, an outage is declared if the messages in the same layer of both MUs cannot be jointly decoded. Therefore, the average throughput can be increased by allowing scenarios where decoding of only one message per layer is allowed. We refer to this approach as "individual outage" decoding, as opposed to the "common outage decoding" used in Proposition 1, and the resulting average throughput can be found in [10, Proposition 5].

IV. Numerical Results

We start by assessing the impact of BC and layered compression on the performance with no fading. To this end, we compare the performance of the proposed scheme with five layers with special cases consisting of a reduced number of layers per user. Specifically, we consider a one layer strategy with $\lambda_1 = 1$, two two-layer strategies, namely scheme 1 with $\lambda_1 + \lambda_5 = 1$ and scheme 2 with $\lambda_1 + \lambda_2 = 1$, and a three layer strategy with $\lambda_1 + \lambda_2 + \lambda_5 = 1$. In most considered instances, we found no significant gain in using the four-layer strategy $(\lambda_1 + \lambda_2 + \lambda_4 + \lambda_5 = 1)$ over the three layer strategy, and hence this strategy is not presented. We also compare the performance of separate and joint decompression corresponding to the performance characterized in Proposition 1 and [10, Proposition 2], respectively, along with an upper bound derived in [10, Sec. III-B] by assuming full knowledge of the backhaul states at all nodes and by leveraging cut-set arguments and [12, Theorem 2]. Fig. 3 shows the average throughput, optimized over the power allocation parameters, versus the probability p of the each backhaul link to be in

$$\mathcal{R}_j \triangleq \Bigg\{ R_{1,j} \leq \log\det\left(\mathbf{I} + \lambda_j P \mathbf{A}_1 \left[\lambda_2 P (\mathbf{A}_1 + \mathbf{A}_2) \mathbb{1}_{\{j=1\}} + \mathrm{diag}\left(f_1(C_1), f_2(C_2)\right)\right]^{-1}\right),$$
$$R_{2,j} \leq \log\det\left(\mathbf{I} + \lambda_j P \mathbf{A}_2 \left[\lambda_2 P (\mathbf{A}_1 + \mathbf{A}_2) \mathbb{1}_{\{j=1\}} + \mathrm{diag}\left(f_1(C_1), f_2(C_2)\right)\right]^{-1}\right),$$
$$R_{1,j} + R_{2,j} \leq \log\det\left(\mathbf{I} + \lambda_j P (\mathbf{A}_1 + \mathbf{A}_2) \left[\lambda_2 P (\mathbf{A}_1 + \mathbf{A}_2) \mathbb{1}_{\{j=1\}} + \mathrm{diag}\left(f_1(C_1), f_2(C_2)\right)\right]^{-1}\right) \Bigg\} \quad (11)$$

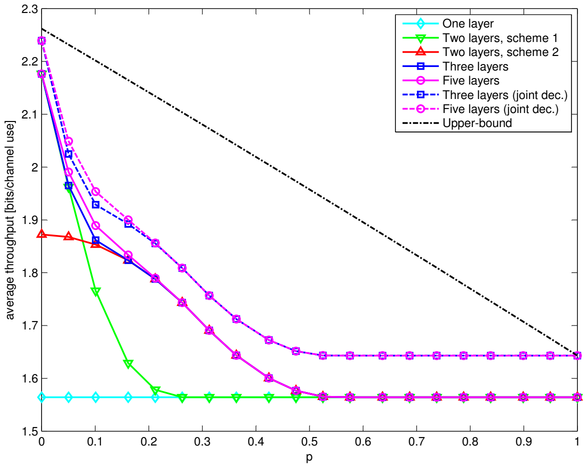

Fig. 3. Average throughput T versus p for $P = 10dB, \alpha = 0.3, C = 1$ bits/channel use and $\Delta C = 0.5$ bits/channel use.

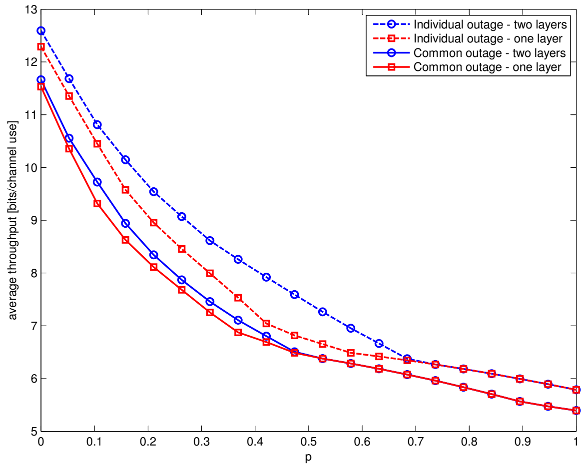

Fig. 4. Average throughput T versus p for $P = 30dB, \alpha = 0.3, C = 4$ bits/channel use and $\Delta C = 6$ bits/channel use.

the low-capacity state $C_j = C$ for $P = 10$dB, $\alpha = 0.3$, $C = 1$ bits/channel use and $\Delta C = 0.5$ bits/channel use. We observe that increasing the number of layers leads to relevant throughput gains and that the same is true of joint decompression versus separate compression.

We now turn to the performance achievable in the presence of quasi-static fading. Figure 4 shows the average throughput, optimized over the power allocation parameters and choice of rates $\{R_{j,1}, R_{j,2}\}_{j=1}^{2}$, versus the probability p of each backhaul link to have capacity C for $P = 30dB, \alpha = 0.3, C = 4$ bits/channel use and $\Delta C = 6$ bits/channel use. The upper bound obtained with full channel and backhaul state information is not shown given that it is not tight for any values of p. As expected, one-layer strategies are outperformed by two-layer strategies and individual-outage based decoding outperforms common-outage based decoding. Note that the performance gain of BC, i.e., of using two layers, is apparent even when $p = 0$, that is, when no backhaul link uncertainty occurs. This is because BC still allows the negative effects of the uncertainty about the fading channels to be alleviated. It is also noted that, similar to the non-fading case of Fig. 3, for p large enough, no performance gain is accrued by using BC. In fact, when p is large, the backhaul is often in the low-capacity state and hence noise due to compression dominates the performance, reducing the gains of BC.

V. Concluding Remarks

In delay-constrained applications, it is often unrealistic to assume transmit channel state information. In a cloud radio access system, this calls for robust transmission strategies both in the first hop between the MUs and the BSs and in the second hop consisting of the backhaul links between BSs and RCP. In this paper, we have proposed such a robust transmission strategy based on BC at the MUs and layered compression at the BSs. The analysis and numerical results reveal the importance of BC and layered compression, especially when coupled with distributed source coding, in opportunistically leveraging advantageous channel and backhaul conditions.

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