Enhancing Uplink Throughput via Local Base Station Cooperation

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***Abstract*—Joint decoding at the base stations of a cellular wireless network enables inter-cell interference mitigation, thus enhancing the system throughput. However, deployment of joint multicell decoding depends critically on the availability of backhaul links connecting the base stations to a central processor. This work studies a scenario in which finite-capacity unidirectional backhaul links exist only between base stations belonging to adjacent cells. Relying on a linear Wyner-type cellular model with no fading, achievable rates are derived for the two scenarios in which the base stations are endowed only with the codebooks of local (in-cell) mobile stations, or also with the codebooks used in adjacent cells. The analysis sheds light on the impact of codebook information, decoding delay and network planning (frequency reuse), on the performance of multicell processing as enabled by local and finite-capacity backhaul links. Analysis in the high-SNR regime and numerical results validate the main conclusions.**

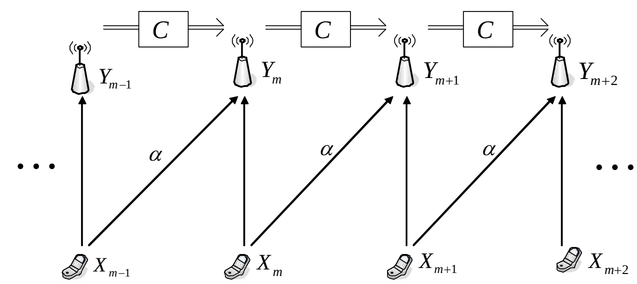

Fig. 1. Uplink of a cellular system with local cooperation between adjacent BSs via finite-capacity links of capacity C.

I. Introduction

An effective solution to deal with interference in infrastructure networks is to have the base stations (BSs) "cooperate" in encoding or decoding for downlink or uplink, respectively (multicell processing). This approach enables high frequency reuse factors and thus promises to greatly improve the spectral efficiency. Deployment of multicell processing depends critically on the topology and quality of the backhaul links connecting the BSs. Early analyses of the performance of such technology were based on the assumption of global and ideal (error-free, infinite-capacity) connections between any BS and a central processor. While these assumptions are reasonable in a small-scale infrastructure system, they become hardly realistic in a large-scale network (e.g., a cellular 3G network), thus calling for approaches that alleviate these demands. As a result, three more practical scenarios have been considered: (*a*) *local connectivity*: BSs are connected only if belonging to adjacent cells, via ideal backhaul links [2]; (*b*) *restricted connectivity to a central processor*: only a subset of BSs is connected to a central processor, via ideal backhaul links [3]; (*c*) *global but finite-capacity connectivity to a central processor*: all the BSs are connected to a central processor but via finite-capacity links [5] [6]. Some works have also considered at various combinations of the previous scenarios [4] [7].

In this paper, we consider the uplink of an infrastructure network modelled according to a standard linear Wyner-type model (see Fig. 1), where cooperative decoding at the BSs is enabled by *local and finite-capacity backhaul links.* In other words, the considered model assumes both local connectivity (as in (*a*)) and finite-capacity backhaul links (similarly to (*c*)). Achievable rates are derived under different assumptions concerning codebook information and directionality of the backhaul links. The derived results shed light on the role of the above mentioned assumptions and of decoding delay in the ability of cooperative decoding to effectively cope with inter-cell interference. In this conference paper, results are stated without proof. For full proof and further results, we refer the reader to [12]. Finally, we notice that the recent paper [13] has considered in parallel a similar scenario given by a two-user Z-channel with finite-capacity cooperation at the receivers' side.

II. System Model

We concentrate on the uplink of a Wyner-type "soft-handoff" cellular model with intra-cell TDMA and no fading (see Fig. 1) as studied in (see [6] for references). Accordingly, one user is active at any given time in any cell (intra-cell time-division multiple-access (TDMA)), and the signal received by the mth BS is ($m = 0, ..., M-1$):

$$Y_m = X_m + \alpha X_{m-1} + Z_m, \tag{1}$$

where X_m represent the complex symbol transmitted by the mth mobile station (MS), Z_m is unit-power white Gaussian noise: $E[Z_m Z^*_{m+k}] = \delta_k$ (time dependence is omitted for simplicity of notation), and $\alpha \in [0, 1]$ is the inter-cell channel gain. We consider a per-MS *short-term* power constraint

$\|\mathbf{X}_m\|^2 \leq n'P$, where $\mathbf{X}_m$ is the sequence of n (complex) channel symbols transmitted by the mth MS during the current coding block (which spans n complex dimensions)[1], and $n' \leq n$ is the number of non-zero entries in $\mathbf{X}_m$ (to account for time-sharing techniques). The channel parameter α is assumed to be known to all the involved terminals. Moreover, we will focus on the case in which the number of cells is large, $M \to \infty$, as in most of the works in this area (see, e.g., [9]). We assume that adjacent BSs are connected by an error-free unidirectional link of capacity C as in Fig. 1. More precisely, a link connect any mth BS to the $(m+1)$th. It should be noted that this choice is well suited to exploit the structure of the channel, where a signal generated by the MS in the mth cell affects the signal received by the $(m+1)$th BS. Extension to bidirectional links is provided in [12]. We emphasize that these backhaul links are orthogonal to the main uplink channel (i.e., we consider out-of-band signalling).

Any mth MS has a rate-R message W_m, selected with equal probability from the set $\{1, ..., 2^{nR}\}$, to deliver to the local (mth) BS. Encoding is carried out via a mapping of the message W_m to a sequence of n complex channel symbols $\mathbf{X}_m$. A mapping between message set $\{1, ..., 2^{nR}\}$ and codewords $\mathbf{X}_m(w_m)$ with $w_m \in \{1, ..., 2^{nR}\}$ is referred to as a *channel codebook*. The rate R, measured in bit/ channel use (or equivalently[2] bit/ sec/ Hz), is defined as *per-cell rate*.

Different assumptions will be made regarding the information available at the BS about the M codebooks used by the M MSs. In particular, we consider two scenarios: (a) *Local codebook information*: Each mth BS knows only the codebook used by the local (mth) MS (Sec. IV); and (b) *Two-cell codebook information:* Each mth BS knows not only the codebook used by the mth MS, but also that used by the $(m-1)$th MS (Sec. V). For communication over the finite-capacity links between BSs, it is assumed that the two BSs at the ends of each link, say the one connecting the mth with the $(m+1)$th BS, share knowledge of a mapping between the index set $\{1, 2, ..., 2^{nR'}\}$ with $R' \leq C$ and an appropriately defined set, to be differently specified for different transmission techniques. The link will be operated by sending an index $i_m \in \{1, 2, ..., 2^{nR'}\}$ from the mth BS to the $(m+1)$th (which requires $R' \leq C$ bits per channel use). Further details will be provided when discussing specific techniques. We will refer to these mappings as *backhaul codebooks*.

III. Reference results

In this section, we first discuss achievable rates that do not require cooperative decoding at the BSs ($C = 0$), and then an upper bound on the performance achievable with cooperation. Starting with the non-cooperative case, a fist simple achievable rate can be obtained by *Single-Cell Processing* (SCP), where decoding is performed locally by treating inter-cell signals as interference, leading to a per-cell achievable rate

$$R_{SCP} = \log\left(1 + \frac{P}{1+\alpha^2 P}\right). \tag{2}$$

If network planning is possible (as in conventional cellular systems), this allows inter-cell interfering signals to be assigned orthogonal resources: in the model at hand (recall Fig. 1) this can be done by scheduling even and odd-numbered cells on orthogonal halves of the coding block (or frequency bandwidth). This approach is defined in [1] as Inter-Cell Time Sharing (ICTS) and yields a per-cell rate of

$$R_{ICTS} = \frac{1}{2}\log(1+P), \tag{3}$$

since every MS is active half of the time and does not experience inter-cell interference.

We derive now an upper bound to the performance achievable with cooperative decoding by considering the ideal case where global and ideal (error-free, infinite-capacity) connections exist between any BS and a central processor. This leads to the upper bound $R \leq R'_U$ (see [3]) where

$$R'_U = \log_2\left(\frac{1 + AP + \sqrt{1 + 2AP + B^2P^2}}{2}\right), \tag{4}$$

with $A = 1 + \alpha^2$ and $B = 1 - \alpha^2$. A better upper bound is derived in [12] as $R \leq \min\{R'_U,\, R''_U\}$ with

$$R''_U = \frac{1}{2}\left[\log(1+P) + \log\left(1 + \frac{P}{1+\alpha^2 P}\right)\right] + C. \tag{5}$$

When discussing the performance of different schemes as compared to the bounds above we will make use of asymptotic measures to get further insight. For reference, considering at first non-cooperative schemes, SCP is easily seen to be *interference-limited,* that is, the corresponding per-cell rate R_{SCP} (3) saturates for $P \to \infty$ to $R_{SCP} \to \log\left(1 + 1/\alpha^2\right)$. On the other hand, ICTS shows a non-interference-limited behavior with per-cell *multiplexing gain* of $1/2$, that is, $\lim_{P\to\infty} R_{ICTS}/\log P = 1/2$. From the upper bound (5), it is seen that, for a fixed backhaul capacity C, the maximum multiplexing gain is indeed achieved by ICTS and equals $1/2$.

IV. Local Codebook Information

In this section, we study a scenario in which information about the channel codebook used by any given mth MS is assumed to be present only at the local (mth) BS (*local codebook information*). For the transmission strategies considered here, the channel codebooks are assumed to be independently and randomly generated (symmetric complex) Gaussian with 2^{nR} independent and identically distributed (i.i.d.) codewords $\mathbf{X}_m(w_m)$ and average power $E[|X_m|^2] = P$. Instead, the backhaul codebooks consist of quantization codebooks to be specified below.

[1]Throughout the paper, bold symbols denote $n \times 1$ vectors, with entries given by the corresponding ordinary-font letters.

[2]The equivalence holds exactly if transmission waveforms with no excess bandwidth are selected.

A. Codeword Compression (CC)

Here we propose a cooperative decoding strategy at the BSs for the scenario of local codebook information. The idea is to perform successive decoding starting with the first ($m = 0$) BS and ending with the last ($m = M$) BS. Successive decoding entails that, once the mth BS has decoded its local message as $\hat{W}_m$, it can compress its decided codeword $\mathbf{X}_m(\hat{W}_m)$ via a rate-C quantization codebook (the backhaul codebook) and send the corresponding index $i_m \in \{1, 2, ..., 2^{nC}\}$ over the backhaul link to the $(m+1)$th BS. The latter then proceeds to decode its local message W_{m+1} based on the received signal $\mathbf{Y}_{m+1}$ (1) and the quantized codeword $\mathbf{X}_m(\hat{W}_m)$ received over the backhaul link. The procedure repeats similarly for all the BSs. We refer to this scheme as Codeword Compression (CC).

Proposition 1. The following rate is achievable with Codeword Compression (CC):

$$R_{CC} = \log\left(1 + \frac{P}{1 + \alpha^2 P\left(1 - \frac{1}{1 + \frac{1}{1 + \frac{\alpha^2 P}{1+P}} \frac{1}{2^C - 1}}\right)}\right). \quad (6)$$

Moreover, enabling ICTS, the maximum achievable rate with CC is $R_{CC-ICTS} = \max\{R_{CC},\, R_{ICTS}\}$.

Remark 1. Some comments on (6) are in order. If we let $P \to \infty$, we can show that R_{CC} tends to a constant value, confirming that the absence of joint decoding and ICTS leads to an interference-limited rate for any finite C [12]. If we let $C \to \infty$, perfect interference cancellation is possible, and $R_{CC} \to \log(1 + P)$: therefore, in the regime $C \to \infty$, the CC scheme is not interference-limited and achieves the multiplexing gain of one of the upper bounds with full cooperation (4), even without deploying ICTS[3].

B. Limiting the Decoding Delay

Here we consider a few techniques that, unlike the CC approach discussed above, do not have the drawback of a large decoding delay, which is caused in CC by successive decoding at the BSs. We emphasize that the decoding delay is defined as the number of previous BSs, indexed by $m - k$, that have to decode the corresponding messages W_{m-k} in order for a given mth BS to be able to decode its own message W_m. Throughout this section, we focus primarily on the scenario in which ICTS is not enabled, since the impact of ICTS easily follows from the previous section.

[3]If one lets the $(m + 1)$th BS be the intended recipient of the message of the mth MS (this may be reasonable as the BSs are typically connected to data or voice network), it can be readily seen that a similar technique based on successive decoding can even surpass the rate of $\log(1 + P)$ when C is large enough. In fact, it is enough for the mth BS to quantize and forward the received signal over the backhaul (this will incur no penalty due to $C \to \infty$) and for the $(m + 1)$th BS to combine the received signals over the backhaul and the channel before decoding to obtain a rate $\log(1+\alpha^2 P/(1+P)+P) > \log(1+P)$ for $C \to \infty$. For finite C, one can see that there exists a minimum value of C, say C^*, such that for $C \geq C^*$ it is convenient to assign message m to BS $m + 1$.

A first practical solution to the problem of delay would be to reduce the rate of given regularly spaced MSs, say at cells kD with a fixed integer D and $k = 0, 1, 2, ...$, to a value smaller than or equal to R_{SCP} (2). This way, the reduced-rate messages W_{kD} can be decoded at the corresponding local (kDth) BSs without delay by treating inter-cell interference as noise, and successive decoding as in CC can be carried out for the other cells with a *maximum* decoding delay of $D-1$. The corresponding per-cell rate is given by the following proposition.

Proposition 2. The rate achievable with the CC transmission scheme modified to have a maximum decoding delay of $D-1$ is given by

$$R_{CC}^{(D)} = \frac{D-1}{D} R_{CC} + \frac{1}{D} R_{SCP}. \quad (7)$$

Remark 2. The CC scheme with maximum decoding delay $D - 1$ that achieves (7) generalizes both the CC introduced in the previous section (which is a special case with $D \to \infty$) and the baseline strategy of SCP, which leads to R_{SCP} (2) (for $D = 1$). Moreover, if ICTS is enabled, the maximum achievable rate is easily shown to be $R_{CC-ICTS}^{(D)} = \max\{R_{CC}^{(D)}, R_{ICTS}\}$.

Remark 3. The asymptotic performance of the reduced-delay version of CC can be easily derived from Remark 1. For instance we have that $\lim_{P\to\infty} R_{CC}^{(D)} = (D - 1)/D \cdot \lim_{P\to\infty} R_{CC} + 1/D \cdot \log(1 + 1/\alpha^2)$, where the first term is obtained from Remark 1, quantifying the performance in the interference-limited regime. Moreover, by letting $C \to \infty$ first, it is easily seen that for any finite delay $D > 1$ this scheme is non-interference-limited, and its multiplexing gain is given by $(D - 1)/D$, which tends to the optimal value of one for $D \to \infty$ (see also Remark 1).

1) Schemes with Zero-Decoding Delay: While for sufficiently large values of D the approach described above leads to a rate (7) which is quite close to R_{CC} (6), it is also of interest to investigate schemes with zero decoding delay. This is easily accomplished by having each mth BS compress and forward the received signal $\mathbf{Y}_m$ (instead of the decoded codeword $\mathbf{X}_m(\hat{W}_m)$). In this case, the backhaul quantization codebook is then used for the purpose of compressing $\mathbf{Y}_m$. We define this transmission strategy as Signal Compression (SC). Notice that, with SC, it makes sense to consider forwarding towards either the right ($(m+1)$th BS, as throughout the paper) or the left ($(m-1)$th) BS. It is emphasized that in this latter case we are exploring a different system with respect to Fig. 1, where the unidirectional backhaul links have the opposite direction.

Proposition 3. The following rate is achievable with Signal Compression (SC) by exploiting rightward backhaul links (as in Fig. 1):

$$R_{SC}^{(R)} = \log\left(1 + \frac{P}{1 + \alpha^2 P\left(1 - \frac{1}{1+\alpha^2+(1+\sigma^2)/P}\right)}\right), \quad (8)$$

while with leftward backhaul links the SC scheme achieves the rate

$$R_{SC}^{(L)} = \log\left(1 + \frac{P}{\alpha^2 P + 1} + \frac{\alpha^2 P}{P + 1 + \sigma^2}\right), \qquad (9)$$

with

$$\sigma^2 = \frac{P(1+\alpha^2) + 1 - \alpha^2 P^2/(P(1+\alpha^2)+1)}{2^C - 1}. \qquad (10)$$

Remark 4. Considering the asymptotic regime of $P \to \infty$, as shown in [12], the interference-limited performance gap between the CC and SC approaches increases, and thus the value of allowing decoding delay becomes more pronounced. To pursue this further, let us take first $C \to \infty$, and recall from Remark 3 that, in this case, the CC scheme is not interference-limited as long as $D > 1$ (i.e., at least one unit of decoding delay is allowed). It can be instead shown that SC (that is, zero decoding delay) is interference-limited [12].

V. Two-cell Codebook Information

In this section, we investigate the scenario in which the channel codebook employed by a given mth MS is known not only at the local mth BS but also at the $(m+1)$th. As will be discussed in the sequel, this further information allows: (*i*) to perform joint decoding of the local message W_m and of (possibly part of) the interfering message W_{m-1} at the mth BS in the spirit of [10]; and (*ii*) more sophisticated quantization strategies on the backhaul link that exploit the side information available at the receiving BS regarding the channel codebook.

A. Decision Compression (DC)

We first investigate a successive decoding strategy that differs from the CC technique described in Sec. IV in that: (*i*) joint decoding of messages W_{m-1} and W_m is carried out at each mth BS; and (*ii*) instead of compressing the decided codeword $\mathbf{X}_m(\hat{W}_m)$, any mth BS bins (compresses) directly the decided message $\hat{W}_m$, exploiting the fact that the channel codebook $\mathbf{X}_m(\hat{W}_m)$ is known at the $(m+1)$th BS. It is remarked that with this first technique, which we refer to as Decision Compression (DC), the *entire* interfering message W_{m-1} is decoded at the mth BS. In the next subsection, we will study a generalized scheme that alleviates this requirement following [10]. As far as the channel codebooks are considered, we assume as in Sec. IV that standard Gaussian channel codebooks $\mathbf{X}_m(w_m)$ with average power P and rate R are available at the MSs. As for the backhaul codebooks, here they consist of mappings between the index set $\{1, 2, ..., 2^{n\min\{R,C\}}\}$ and a set of bins of the message set $\{1, ..., 2^{nR}\}$, each bin having size $2^{n(R-\min\{R,C\})}$.

To elaborate, assume at first $R > C$. The $(m-1)$th BS decodes the message W_{m-1} and sends the index of the bin in which message W_{m-1} falls to the mth BS. The mth BS then jointly decodes W_{m-1} and W_m based on the received signal $\mathbf{Y}_m$ and the bin index i_{m-1} received over the backhaul link. If $R \leq C$, then the entire message W_{m-1} can be sent over the backhaul link and the interference-free rate $R = \log(1+P)$ is achievable.

Proposition 4. The following rate is achievable with Decision Compression (DC):

$$R_{DC} = \min\left\{ \begin{array}{c} \log(1+P),\ \log\left(1+\alpha^2 P\right) + C, \\ \frac{1}{2}\log\left(1 + (1+\alpha^2)\, P\right) + \frac{C}{2} \end{array} \right\}. \qquad (11)$$

Moreover, if ICTS is enabled, the maximum rate achievable with DC is $R_{DC-ICTS} = \max\{R_{DC}, R_{ICTS}\}$.

Remark 5. It is noted that the DC scheme discussed above and all the schemes presented in this section suffer from the same problem with the decoding delay as the CC technique discussed in the previous section. However, similarly to CC, this problem can be easily alleviated by reducing the rate of given, regularly placed, MSs, as per Proposition 2. This gives rise to modified transmission schemes with controllable (maximum) decoding delay $D-1$ and achievable rates that can be easily inferred from Proposition 2. For instance, the DC scheme modified to guarantee a decoding delay of $D-1$ units leads to an achievable rate $R_{DC}^{(D)} = \frac{D-1}{D}R_{DC} + \frac{1}{D}R_{SCP}$.

Remark 6. Due to the joint decoding carried out at each BS, the DC scheme is non-interference-limited for any fixed value of C, even without ICTS. This is unlike the approaches discussed in Sec. IV, in which joint decoding was ruled out by the absence of information about the interfering MS's codebook. In particular, it is noted that the multiplexing gain of the DC scheme, with or without ICTS, is 0.5 (or $\frac{D-1}{2D}$ for the reduced-delay version without ICTS discussed in the previous remark). However, assume now that we can let the backhaul capacity scale with P as $C \sim \beta \log P$ with $0 \leq \beta \leq 1$. It is then easy to see from (11) that the multiplexing gain of DC becomes $(\beta+1)/2$, so that, in order to have the optimum multiplexing gain of one, it is enough that the capacity C scales as $\log P$ ($\beta = 1$).

B. Decision Compression (DC) with Rate Splitting (RS)

The DC presented in the previous section prescribes joint decoding at any mth BS of both messages W_{m-1} and W_m. This requirement can be quite demanding in scenarios where the inter-cell gain α^2 and the backhaul link capacity C are not large enough, and thus might entail a relevant rate loss. For this reason, it is convenient to consider a more general transmission technique where only part of the interfering MS's message (W_{m-1}) is decoded, according to the rate splitting idea [10]. A full analysis of such a scheme can be found in [12].

VI. Numerical results

In this section, we further corroborate the results derived in the paper via numerical results. Fig. 2 shows the derived achievable rates versus the SNR P for $\alpha^2 = 0.6$ and $C = 3$. The interference-limited behavior of the schemes based on local codebook information, namely CC and SC, is apparent. Moreover, the performance gain of CC over SC measures the advantages of allowing some decoding delay. It is also seen that with two-cell codebook information, i.e., employing the DC (R_{DC}) or the DC-RS scheme allows a non-interference limited behavior with multiplexing gain 0.5 to be attained.

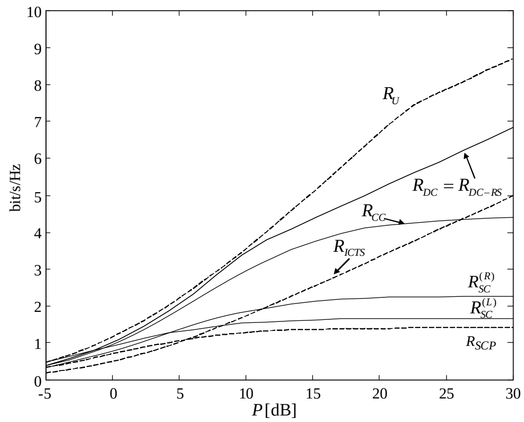

Fig. 2. Achievable rates versus SNR P ($\alpha^2 = 0.6$ and $C = 3$).

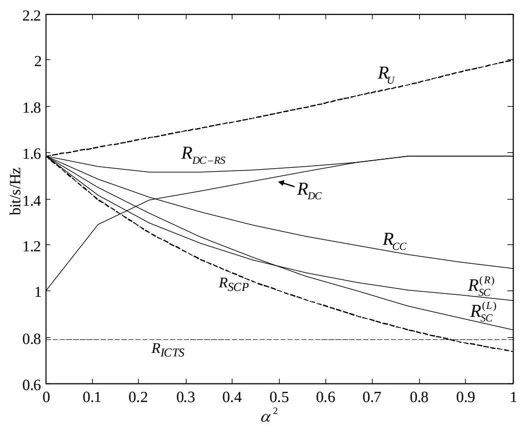

Fig. 3. Achievable rates versus α^2 ($P = 3dB$ and $C = 1$).

Finally, for this specific example, there is no gain in allowing rate splitting with respect to the basic DC scheme so that R_{DC-RS} coincides with R_{DC}.

The advantages of rate splitting over the basic DC scheme are further studied in Fig. 3, where the achievable rates for the system of Fig. 2 are shown versus the inter-cell gain α^2 for $P = 3dB$ and $C = 1$. It can be seen that for low α^2, it is not convenient for each BS to decode the entire message of the interfering cell (that is, to use the basic DC scheme), but rather to employ rate splitting. This fact is apparent in the performance gains of DC-RS with respect to DC for low α^2. For increasing α^2, however, it is clearly advantageous to transmit only common messages and $R_{DC} = R_{DC-RS}$. It is also interesting to observe that, in the presence of local codebook information (R_{CC}, $R_{SC}^{(R)}$ and $R_{SC}^{(L)}$), increasing inter-cell gain α^2 is deleterious for the performance, while this is not the case for DC-based schemes (R_{DC} and R_{DC-RS}), which exploit the side information about the codebook used by the interfering MS.

VII. CONCLUSIONS

In this paper, we have evaluated the potential advantages in terms of achievable per-cell rates that can be harnessed via cooperative decoding at the BSs, under the practical assumption of local and finite-capacity (backhaul) connections between adjacent BSs. The information-theoretic analysis exploits the symmetry of the considered (Wyner-type) channel model to allow compact analytical expressions to be derived and, as a consequence, insight to be obtained. Specifically, we have pointed to the key role of three factors, namely the *decoding delay*, the *knowledge about the channel codebooks* and *rate splitting coding techniques.* All these factors are known to have a minor impact in the presence of a global backhaul connecting all the BSs to a central processor [5] [6].

VIII. ACKNOWLEDGMENT

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