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On Base Station Cooperation Schemes for Downlink Network MIMO under a Constrained Backhaul

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***Abstract*— Next generation mobile comunications systems will most likely employ multi-cell cooperative signal processing schemes, often referred to as *network MIMO*, as these are known to effectively combat inter-cell interference and improve system fairness and spectral efficiency. A major downside of such schemes is, however, the large extent of backhaul infrastructure required for the information exchange between cooperating base stations. In this paper, we observe a cooperative downlink transmission from two base stations to two terminals under different extents of available backhaul capacity. We adapt some well-known concepts from the *Gaussian interference channel* and observe a variety of possible cooperation schemes. We observe that it is beneficial to use an adaptive cooperation concept, where the base stations exchange either the data to be jointly transmitted itself or partially precoded and compressed signals, depending on the instantaneous channel realization.**

I. Introduction

Next generation mobile communications systems, aiming at a high spectral efficiency and thus a maximum spectrum reuse, will require means of inter-cell interference cancellation. One promising option is to use multi-cell joint detection or joint transmission, initially proposed by e.g. [1], [2], exploiting interference rather than treating it as noise. For the downlink, optimistic capacity bounds for large clusters of cooperating cells have been derived in e.g. [3].

A main problem connected to multi-cell signal processing is, however, the additional backhaul traffic required between cooperating base stations. We have initially investigated the option of serving only subsets of terminals with joint signal processing [4], or partitioning a cellular network into small subsystems where these schemes can be applied locally [5], in both cases already yielding a strong reduction of backhaul.

We now want to explore information-theoretical limits of downlink joint transmission under a constrained backhaul. We observe a toy scenario where two base stations (BSs) transmit to two terminals. When no cooperation between the BSs is possible, our scenario resembles a so-called *Gaussian interference channel*, which was initially investigated in [6], [7], and where transmission concepts based on superposition coding were found to extend the rate region in [8], [9]. When limited backhaul enables some extent of cooperation, the scenario resembles an *interference channel with partial transmitter cooperation*, which was studied in e.g. [10] for the case of *strong interference* (i.e. the link from the interfering BS to a terminal is stronger than the link from the home BS), and in [11], [12] for the opposite, the *weak interference* case, involving concepts of *dirty-paper coding* [13]. For the case of infinite cooperation, our scenario resembles the well-known *broadcast channel*, for which the rate region has been established in e.g. [14]. It has to be noted, however, that our scenario is different from an interference channel in the way that each terminal can be served by either of the two BSs.

In this work, we analyze the performance of joint transmission under arbitrary channel realizations (hence considering both weak and (unilaterally) strong interference cases), and under different extents of available backhaul. We consider three different schemes of information exchange that can take place between the BSs, including and extending schemes observed in [11] or in [15] for a Wyner model. Monte Carlo simulation results show that a system performing adaptive cooperation based on the channel realization is beneficial.

In section II, we define our system model, and explain our considered cooperation schemes in section III. Details on the achievable rates and performance are provided in sections IV and V, respectively, and the paper is completed with simulation results and conclusions in sections VI and VII, respectively.

II. System Model

In this paper, we consider a downlink transmission from two base stations (BSs) A and B with any number of transmit antennas N_{bs} each to two terminals a and b with one receive antenna each, as depicted in figure 1. We assume the transmission takes place through a frequency-flat channel, for example a single sub-carrier of an OFDM system, described through

$$\mathbf{H} = \begin{bmatrix} \mathbf{h}_a^A & \mathbf{h}_b^A \\ \mathbf{h}_a^B & \mathbf{h}_b^B \end{bmatrix}, \tag{1}$$

where $\mathbf{h}_a^A$, for instance, describes the channel coefficients between BS A and terminal a, and $\mathbf{h}_a^A, \mathbf{h}_b^A, \mathbf{h}_a^B, \mathbf{h}_b^B \in \mathbb{C}^{[N_{bs}\times 1]}$. We assume that both BSs have perfect knowledge of $\mathbf{H}$, and that all four entities are perfectly synchronized in time and frequency, such that the transmission is free of inter-symbol and inter-carrier interference. Furthermore, the BSs are connected through an error-less, but capacity-limited backhaul link. We consider transmission schemes based on superposition coding, where the available transmit power is invested into multiple messages $U_a, U_b, W_a, W_b, J_a, J_b$. Each message consists of N

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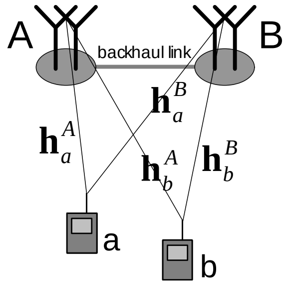

Fig. 1. Downlink transmission considered in this paper.

symbols consecutively transmitted over the channel, hence e.g. $U_a = \{s_{U_a}^{[1]}, s_{U_a}^{[2]}, \cdots, s_{U_a}^{[N]}\}$, and we define that:

- Messages U_a and U_b are transmitted *conventionally* from BSs A and B with powers P_{U_a} and P_{U_b} to terminals a and b, respectively, for $N_{bs} > 1$ using local precoding.
- Messages W_a and W_b are also transmitted *conventionally* from BSs A and B with powers P_{W_a} and P_{W_b}, respectively, but are decoded by *both* terminals. These are hence *common messages* as considered in [8], [9].
- Messages J_a and J_b are transmitted *jointly* from both BSs to a and b, respectively, with powers P_{J_a} and P_{J_b}, employing dirty-paper coding (DPC) [13]. We write $P_{J_a} = P_{J_a}^A + P_{J_a}^B$ and $P_{J_b} = P_{J_b}^A + P_{J_b}^B$ to distinguish the transmit power portions of the messages transmitted from BSs A and B. We will later observe schemes where the transmission of J_a and J_b is subject to quantization noise, where $\forall K \in \{A, B\}, j \in \{a, b\} : q_j^K$ denotes the number of quantization bits used when transmitting each symbol connected to message J_j from BS K.

In the sequel, we will use the following notation:

$$\begin{aligned} \mathcal{S}_{all} &= \{U_a, U_b, W_a, W_b, J_a, J_b\} : \text{all messages} \\ \mathcal{S}_a &= \{U_a, W_a, W_b, J_a\} : \text{messages decoded by } a \\ \mathcal{S}_b &= \{U_b, W_a, W_b, J_b\} : \text{messages decoded by } b \end{aligned}$$

The transmission of each symbol can be stated as

$$\mathbf{y}^{[n]} = \mathbf{H}^T \left(\begin{bmatrix} \mathbf{w}_a^A & 0 \\ 0 & \mathbf{w}_b^B \end{bmatrix} \begin{bmatrix} \sqrt{P_{U_a}} s_{U_a}^{[n]} + \sqrt{P_{W_a}} s_{W_a}^{[n]} \\ \sqrt{P_{U_b}} s_{U_b}^{[n]} + \sqrt{P_{W_b}} s_{W_b}^{[n]} \end{bmatrix} + \begin{bmatrix} \sqrt{P_{J_a}^A \alpha_a^A} \bar{\mathbf{w}}_a^A & \sqrt{P_{J_b}^A \alpha_b^A} \bar{\mathbf{w}}_b^A \\ \sqrt{P_{J_a}^B \alpha_a^B} \bar{\mathbf{w}}_a^B & \sqrt{P_{J_b}^B \alpha_b^B} \bar{\mathbf{w}}_b^B \end{bmatrix} \begin{bmatrix} s_{J_a}^{[n]} \\ s_{J_b}^{[n]} \end{bmatrix} \right) + \mathbf{n}^{[n]} + \mathbf{d}^{[n]}, \quad (2)$$

where $\mathbf{y}^{[n]} \in \mathbb{C}^{[2\times 1]}$ are the signals received at the terminals, $\mathbf{w}_a^A$ and $\mathbf{w}_b^B$ are the precoding vectors used for the conventional transmission of messages U_a, U_b, W_a and W_b. $\bar{\mathbf{w}}_a^A$, $\bar{\mathbf{w}}_b^A$, $\bar{\mathbf{w}}_a^B$, $\bar{\mathbf{w}}_b^B$ are the precoding vectors used for the joint transmission of messages J_a and J_b. All precoding vectors in Eq. (2) fulfill $\forall K \in \{A, B\}, j \in \{a, b\} : \mathbf{w}_j^K, \bar{\mathbf{w}}_j^K \in \mathbb{C}^{[2\times 1]}$ and $(\mathbf{w}_j^K)^H \mathbf{w}_j^K = (\bar{\mathbf{w}}_j^K)^H \bar{\mathbf{w}}_j^K = 1$, and all transmitted symbols are mutually uncorrelated Gaussian scalars with $\forall X \in \mathcal{S}_{all}$: $E_n\{s_X^{[n]}\} = 0$ and $E_n\{(s_X^{[n]})^H s_X^{[n]}\} = 1$. Term $\mathbf{n}^{[n]} \in \mathbb{C}^{[2\times 1]}$ denotes thermal noise plus interference from outside the system as received by the terminals, assumed to be uncorrelated Gaussian with $E_n\{\mathbf{n}^{[n]}(\mathbf{n}^{[n]})^H\} = \sigma^2 \mathbf{I}$. $\mathbf{d}^{[n]} \in \mathbb{C}^{[2\times 1]}$ denotes quantization noise with $E_n\{\mathbf{d}^{[n]}(\mathbf{d}^{[n]})^H\} = \text{diag}(\sigma_a^2, \sigma_b^2)$. The latter variances and the scaling factors $\forall K \in \{A, B\}, j \in \{a, b\}$: α_j^K, assuring that the power of a signal before quantization is equal to the power after quantization plus that of the quantization noise, will be explained later.

III. Cooperation Schemes

In this paper, we consider the following three specific cooperation schemes between the two base stations:

- Jointly transmitted messages J_a and J_b are known to both BSs, either because the network provides these to both BSs, or because they are exchanged over the backhaul. In both cases, we count the corresponding additional network traffic as *backhaul*, assuming it leads to a similar increase in cost. Both BSs, knowing the messages and the channel matrix, can perform joint transmission and DPC redundantly, free of quantization noise and without further exchange of information over the backhaul. We call this scheme, also considered in [11], **unquantized message based cooperation** (**UMC**).
- The network provides only one BS with both messages J_a and J_b. As the other BS receives no information about these messages, the network traffic so far is the same as that of a conventional system. The knowledgeable BS now performs DPC, quantizes and forwards the signals to be transmitted from the other BS via the backhaul. DPC can be applied to benefit either terminal a or b, but joint transmission is subject to quantization noise. We refer to this scheme, similar to the concept of central encoding in [15], as **quantized signal based cooperation** (**QSC**).
- Finally, we consider the case where the network provides either message J_a or J_b to both of the BSs (where the increase in traffic compared to a conventional system is again counted as backhaul), and the other one to only one BS. Both BSs perform joint transmission for the message they both know, whereas for the other message, the BS knowing both messages performs DPC, quantizes and forwards the signals connected to the message and to be transmitted from the other BS via the backhaul. This introduces quantization noise for one of the two terminals. We refer to this as **mixed UMC / QSC schemes**.

In general, we have to consider these aspects of DPC:

- DPC can make a transmission free of interference from any messages known to the DPC-encoding BS. If, e.g., BS B performs DPC and transmits J_a in order to benefit terminal a, it can remove not only the interference that message J_b poses towards a (assuming J_b is known to B), but also the interference from message U_b.
- However, a terminal that benefits from DPC cannot decode any other messages not included in the DPC transmission. Hence, in the example given before, terminal a cannot profit from DPC while simultaneously exploiting a message U_a originating from A.

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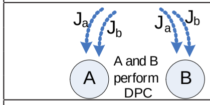
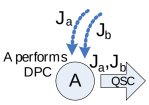
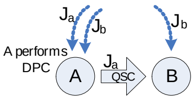
TABLE I

JOINT TRANSMISSION / COOPERATION SCHEMES CONSIDERED IN THIS PAPER.

	Joint transmission / cooperation scheme	No.	Quant. par. q $q_a^A, q_b^A, q_a^B, q_b^B$	Messages transmitted and causing interference / required backhaul
	**UMC**: The network provides both BSs with jointly transmitted messages J_a, J_b and DPC is performed by A, B redundantly. Degr. of freedom: DPC encoding order.	1 2	$\infty, \infty, \infty, \infty$ $\infty, \infty, \infty, \infty$	$\mathcal{S}'=\{J_a, U_b, J_b\}, \mathcal{S}_a^\diamond=\{U_b\}, \mathcal{S}_b^\diamond=\{J_a\}$ $\mathcal{S}'=\{U_a, J_a, J_b\}, \mathcal{S}_a^\diamond=\{J_b\}, \mathcal{S}_b^\diamond=\{U_a\}$ Backhaul: $\beta(\mathbf{q}, R_{J_a}, R_{J_b}) = R_{J_a} + R_{J_b}$
	**QSC**: The network provides one BS with jointly transmitted messages J_a, J_b. This BS performs DPC, quantizes and relays the signals to be transm. from the other BS via the backhaul. Degrees of freedom: Role of the BSs and DPC encoding order.	3 4 5 6	$\infty, \infty, q_a^B, q_b^B$ $\infty, \infty, q_a^B, q_b^B$ $q_a^A, q_b^A, \infty, \infty$ $q_a^A, q_b^A, \infty, \infty$	$\mathcal{S}'=\mathcal{S}_{all}\backslash W_b, \mathcal{S}_a^\diamond=\{U_b\}, \mathcal{S}_b^\diamond=\{U_a, W_a, J_a\}$ $\mathcal{S}'=\{U_a, W_a, J_a, J_b\}, \mathcal{S}_a^\diamond=\{J_b\}, \mathcal{S}_b^\diamond=\{W_a\}$ $\mathcal{S}'=\{J_a, U_b, W_b, J_b\}, \mathcal{S}_a^\diamond=\{W_b\}, \mathcal{S}_b^\diamond=\{J_a\}$ $\mathcal{S}'=\mathcal{S}_{all}\backslash W_a, \mathcal{S}_a^\diamond=\{U_b, W_b, J_b\}, \mathcal{S}_b^\diamond=\{U_a\}$ Backh.: $\beta(\mathbf{q}, R_{J_a}, R_{J_b}) = \min(q_a^A+q_b^A, q_a^B+q_b^B)$
	**Mixed UMC/QSC**: The network provides one BS with *one*, and the other with *both* messages J_a, J_b. Latter BS performs DPC, quant. and relays only the signals connected to the message *not* known to the other BS. Degrees of freedom: Role of the BSs and message benefitting from DPC.	7 8 9 10	$\infty, \infty, q_a^B, \infty$ $q_a^A, \infty, \infty, \infty$ $\infty, \infty, \infty, q_b^B$ $\infty, q_b^A, \infty, \infty$	$\mathcal{S}'=\mathcal{S}_{all}\backslash W_b, \mathcal{S}_a^\diamond=\{U_b\}, \mathcal{S}_b^\diamond=\{U_a, W_a, J_a\}$ $\mathcal{S}'=\{J_a, U_b, W_b, J_b\}, \mathcal{S}_a^\diamond=\{W_b\}, \mathcal{S}_b^\diamond=\{J_a\}$ Backh.: $\beta(\mathbf{q}, R_{J_a}, R_{J_b}) = \min(q_a^A, q_a^B) + R_{J_b}$ $\mathcal{S}'=\{U_a, W_a, J_a, J_b\}, \mathcal{S}_a^\diamond=\{J_b\}, \mathcal{S}_b^\diamond=\{W_a\}$ $\mathcal{S}'=\mathcal{S}_{all}\backslash W_a, \mathcal{S}_a^\diamond=\{U_b, W_b, J_b\}, \mathcal{S}_b^\diamond=\{U_a\}$ Backh.: $\beta(\mathbf{q}, R_{J_a}, R_{J_b}) = R_{J_a} + \min(q_b^A, q_b^B)$

Thus, depending on the cooperation scheme, only a subset of messages $\mathcal{S}' \subset \mathcal{S}_{all}$ may be used, and the extent of interference cancelled through DPC differs. We write the remaining set of interfering messages a terminal j sees as $\mathcal{S}_j^\diamond$, and summarize all observed cooperation schemes and corresponding sets $\mathcal{S}'$ and $\mathcal{S}_j^\diamond$ in Table I.

IV. ACHIEVABLE RATES

We now derive the achievable rates for the transmissions to the two terminals as a function of power allocation $\mathbf{p} = [P_{U_a}, P_{U_b}, P_{W_a}, P_{W_b}, P_{J_a}, P_{J_b}]$ and the number of quantization bits $\mathbf{q} = [q_a^A, q_b^A, q_a^B, q_b^B]$. We use the notation from [9] to state the achievable rate region of all messages as the set of all rate points $\mathcal{R}(\mathbf{p}, \mathbf{q}) = \{(R_{U_a}, R_{U_b}, R_{W_a}, R_{W_b}, R_{J_a}, R_{J_b})\}$ that fulfill $\forall X \in \mathcal{S}_{all} : R_X \geq 0$ and

$$\forall \mathcal{S} \subseteq \mathcal{S}_a, \mathcal{S}^* = \mathcal{S}_a \backslash \mathcal{S} : \sum_{X \in \mathcal{S}} R_X \leq I(Y_a; \mathcal{S}|\mathcal{S}^*)[\mathbf{p}, \mathbf{q}] \tag{3}$$

$$\forall \mathcal{S} \subseteq \mathcal{S}_b, \mathcal{S}^* = \mathcal{S}_b \backslash \mathcal{S} : \sum_{X \in \mathcal{S}} R_X \leq I(Y_b; \mathcal{S}|\mathcal{S}^*)[\mathbf{p}, \mathbf{q}] \tag{4}$$

This notation incorporates the concept of *joint decoding* [9], hence the decoding performance of one terminal is independent of any concrete decoding order used by the other terminal. The transinformation term in Eq. (3) is given as $\forall j \in \{a, b\}$

$$I(Y_j; \mathcal{S}|\mathcal{S}^*)[\mathbf{p}, \mathbf{q}] = \log_2 \left(1 + \frac{\sum\limits_{X \in \mathcal{S} \cap \mathcal{S}'} \rho_j^X}{\sum\limits_{X \in ((\mathcal{S}_j \cap \mathcal{S}') \cup \mathcal{S}_j^\diamond) \backslash (\mathcal{S} \cup \mathcal{S}^*)} \rho_j^X + \sigma_j^2 + \sigma^2} \right) \tag{5}$$

where $k \neq j$ and $\forall j \in \{a, b\}, X \in \mathcal{S}_{all}$ the term ρ_j^X expresses the received signal power of message X at terminal j, for which the dependency on $\mathbf{p}, \mathbf{q}$ is omitted for brevity. For the conventionally transmitted messages, these terms are given as

$$\rho_a^{U_a} = P_{U_a} \xi_{aa}^A, \quad \rho_b^{U_a} = P_{U_a} \xi_{ab}^A, \quad \rho_a^{U_b} = P_{U_b} \xi_{ba}^B, \\ \rho_b^{U_b} = P_{U_b} \xi_{bb}^B, \quad \rho_a^{W_a} = P_{W_a} \xi_{aa}^A, \quad \rho_b^{W_a} = P_{W_a} \xi_{ab}^A, \\ \rho_a^{W_b} = P_{W_b} \xi_{ba}^B, \quad \rho_b^{W_b} = P_{W_b} \xi_{bb}^B \tag{6}$$

where $\forall K \in \{A, B\}, \ i, j \in \{a, b\} : \xi_{ij}^K = |(\mathbf{h}_j^K)^T \mathbf{w}_i^K|^2$. For the jointly transmitted messages J_a, J_b, we can state

$$\rho_a^{J_a} = P_{J_a}^A \alpha_a^A \xi_{aa}^A + P_{J_a}^B \alpha_a^B \xi_{aa}^B + \sqrt{P_{J_a}^A P_{J_a}^B \alpha_a^A \alpha_a^B} \bar{\xi}_{aa}^{AB} \tag{7}$$

$$\rho_b^{J_b} = P_{J_b}^A \alpha_b^A \xi_{bb}^A + P_{J_b}^B \alpha_b^B \xi_{bb}^B + \sqrt{P_{J_b}^A P_{J_b}^B \alpha_b^A \alpha_b^B} \bar{\xi}_{bb}^{AB} \tag{8}$$

$$\rho_a^{J_b} = P_{J_b}^A \xi_{ba}^A + P_{J_b}^B \xi_{ba}^B + \sqrt{P_{J_b}^A P_{J_b}^B \alpha_b^A \alpha_b^B} \bar{\xi}_{ba}^{AB} \tag{9}$$

$$\rho_b^{J_a} = P_{J_a}^A \xi_{ab}^A + P_{J_a}^B \xi_{ab}^B + \sqrt{P_{J_a}^A P_{J_a}^B \alpha_a^A \alpha_a^B} \bar{\xi}_{ab}^{AB} \tag{10}$$

In these terms, $\forall K \in \{A, B\}, \ i, j \in \{a, b\} : \bar{\xi}_{ij}^K = |(\mathbf{h}_j^K)^T \bar{\mathbf{w}}_i^K|^2$, and $\bar{\xi}_{ij}^{AB}$ expresses the *beamforming gain* that a joint transmission from BSs A and B targeted towards terminal i poses on terminal j, given as

$$\forall i, j \in \{a, b\} : \ \bar{\xi}_{ij}^{AB} = 2 \cdot \mathrm{Re}\left\{ (\mathbf{h}_j^A)^T \bar{\mathbf{w}}_i^A (\mathbf{h}_j^B)^T \bar{\mathbf{w}}_i^B \right\} \tag{11}$$

Concerning the quantization noise σ_j^2 in Eq. (5), we consider two different quantization schemes. If each BS has one antenna (i.e. $N_{bs} = 1$) and QSC schemes are applied, we assume that the DPC-performing BS calculates the overall precoded signal (w.r.t. J_a, J_b) to be transmitted from the remote BS and quantizes this, such that rate distortion theory [16] yields

$$\sigma_a^2 = P_{J_a}^A 2^{-(q_a^A + q_b^A)} \bar{\xi}_{aa}^A + P_{J_a}^B 2^{-(q_a^B + q_b^B)} \bar{\xi}_{aa}^B \tag{12}$$

$$\sigma_b^2 = P_{J_b}^A 2^{-(q_a^A + q_b^A)} \bar{\xi}_{bb}^A + P_{J_b}^B 2^{-(q_a^B + q_b^B)} \bar{\xi}_{bb}^B \tag{13}$$

and $\forall K \in \{A, B\}, j \in \{a, b\} : \alpha_j^K = 1 - 2^{-(q_a^K + q_b^K)}$. In all other cases, we assume that the DPC-performing BS quantizes and relays the DPC-encoded signals connected to messages J_a, J_b separately, but the precoding vectors from Eq. (2) are applied at the remote BS. We consider this to be both practical and backhaul-efficient, though a more generic quantization approch as in [17] might yield better performance. We use

$$\sigma_a^2 = P_{J_a}^A 2^{-q_a^A} \bar{\xi}_{aa}^A + P_{J_a}^B 2^{-q_a^B} \bar{\xi}_{aa}^B \tag{14}$$

$$\sigma_b^2 = P_{J_b}^A 2^{-q_b^A} \bar{\xi}_{bb}^A + P_{J_b}^B 2^{-q_b^B} \bar{\xi}_{bb}^B \tag{15}$$

and $\forall K \in \{A, B\}, j \in \{a, b\} : \alpha_j^K = 1 - 2^{-q_j^K}$ in these cases.

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A. Calculation of precoding vectors

It is known from e.g. [18] that the calculation of precoding vectors for a downlink transmission according to a sum-rate or common rate metric is difficult due to the non-convexity of the problem. Most authors thus suggest to use uplink/downlink duality, hence to solve an uplink beamforming problem with more amenable mathematical properties, and transform the result back into the downlink. It is e.g. known that under a sum power constraint, any rate point achievable in a dual uplink problem is also achievable in the downlink with the same precoding vectors, but a different power allocation. Furthermore, it has been shown that a downlink under *per-base station* power constraints can be solved through a dual uplink problem with an initially unknown noise covariance matrix [19]. As for our transmission model an optimal calculation would go beyond the scope of the paper, we suggest to use a non-optimal, but strongly simplified calculation of precoding vectors. We assume that both local or joint precoding is performed such that a maximal coherent overlap of signals takes place at the terminal the transmission is targeted to, known as *maximimum ratio transmission*. In this case, all interference coefficients ξ from the last section depend only on the channel $\mathbf{H}$, but not on the chosen power allocation or DPC encoding order etc., and can be stated as

$$\forall K{\in}\{A,B\}, i,j \in \{a,b\} : \xi_{ij}^{K} = \bar{\xi}_{ij}^{K} = \frac{\left|\left(\mathbf{h}_j^K\right)^H \mathbf{h}_i^K\right|^2}{\left|\mathbf{h}_i^K\right|^2}$$
$$\text{and } \bar{\xi}_{ij}^{AB} = 2\frac{\text{Re}\left\{(\mathbf{h}_j^A)^H\mathbf{h}_i^A(\mathbf{h}_j^B)^H\mathbf{h}_i^B\right\}}{|\mathbf{h}_i^A||\mathbf{h}_i^B|} \quad (16)$$

V. Achievable Performance

In [20], we have introduced the concept of *performance regions* that capture both achievable rates and the backhaul required to achieve these rates. An achievable performance region is defined as the set of all rates and backhaul fulfilling

$$\mathcal{P} = \bigcup\{(R_{U_a}{+}R_{J_a}{+}\gamma, R_{U_b}{+}R_{J_b}{+}\delta, \beta(\mathbf{q}, R_{J_a}, R_{J_b})) : \gamma + \delta \leq R_{W_a} + R_{W_b} \wedge (R_{U_a}, R_{U_b}, R_{W_a}, R_{W_b}, R_{J_a}, R_{J_b}) \in \mathcal{R}(\mathbf{p},\mathbf{q})\} \quad (17)$$

where the required backhaul $\beta(\cdot)$ is stated in Table I, and $\bigcup$ denotes the calculation of the convex hull - implying time-sharing along rate and backhaul dimensions - around all performance points based on parameters $\mathbf{p}$ fulfilling

$$\sum_{X\in\mathcal{S}_{all}} P_X \leq P_{max} \textbf{ or } P_{U_a} + P_{W_a} + P_{J_a}^A + P_{J_b}^A \leq P_{max}^A \wedge P_{U_b} + P_{W_b} + P_{J_a}^B + P_{J_b}^B \leq P_{max}^B \quad (18)$$

if we are considering a *sum power constraint* $P_{max} \in \mathbb{R}^+$ or a *per-base-station* power constraint $P_{max}^A, P_{max}^B \in \mathbb{R}^+$, respectively, and for all possible choices of $\mathbf{q}$ according to Table I. Eq. (17) implies that we have the additional degree of freedom that any portion of the common messages W_a, W_b can be attributed to either of the terminals, as both terminals decode them anyway. This concept was also considered in [10].

VI. Simulation Results

A. Simulation Methodology

Even with our simplified calculation of non-optimal precoding vectors, as discussed in section V, it is difficult to determine the performance region for a given channel considering a sufficient number of power allocations $\mathbf{p}$ and quantization schemes $\mathbf{q}$, particularly as the rate expressions in section IV are non-convex in the power parameters. We thus perform a brute-force search over the parameter space at a moderate resolution and determine the cooperation schemes and parameter sets that support the convex hull of the performance region. For these points, we then perform more detailed local searches, determine the supporting points again, such that after a few iterations we obtain results where the power allocation is optimized to a granularity of roughly 1%.

B. An Example Channel

Figure 2 shows the performance region of an example channel $\mathbf{H}{=}[-1.0577{+}0.9077i, 0.4639{+}0.0881i; -0.4479{+}0.3804i, 0.0646 - 1.1627i; -0.4463 + 0.3957i, -0.6226 + 1.4001i; 0.3241{-}0.1441i, 0.8570{-}0.1625i]$ with $N_{bs}{=}2$ for different cooperation schemes, under a sum-power constraint with $P_{max}{=}2$ and $\sigma^2{=}0.1$. In general, we plot the achievable rates of terminals a and b on the x- and y-axis, respectively, and the required backhaul β on the z-axis. The top plots in Fig. 2 show performance regions for the schemes discussed in section III. The lower plots show that different schemes are superior in certain areas of the convex performance hull, whereas the right plot shows the achievable sum rate as a function of backhaul if the common terminal rate is maximized. The cut-set bound resembles the theoretical performance if each bit of backhaul would yield an equal increase in sum rate. We have observed that for UMC schemes, the transmit power for one terminal should either be invested completely into conventional or into joint transmission, but not be split. As a certain backhaul threshold is required to enable these schemes, it is best to operate on a time-share between conventional or joint transmission in regimes of lower backhaul. The same holds for QSC schemes, which require a certain backhaul threshold beyond which the beamforming gain dominates the introduced quantization noise. QSC schemes can outperform UMC schemes especially when one BS has a fairly strong link to both terminals, but UMC is obviously always superior when the available backhaul exceeds the maximum sum rate, as then the scenario resembles a fully cooperative MIMO broadcast channel. The usage of common messages W_a, W_b is not beneficial for the example channel.

C. Monte Carlo Simulations

Figure 3 shows Monte Carlo results with many channel realizations drawn from an i.i.d Rayleigh distribution fulfilling $E\{(\mathbf{h}_a^A)^H\mathbf{h}_a^A\} = E\{(\mathbf{h}_b^B)^H\mathbf{h}_b^B\} = N_{bs}$ and $E\{(\mathbf{h}_b^A)^H\mathbf{h}_b^A\} = E\{(\mathbf{h}_a^B)^H\mathbf{h}_a^B\}{=}N_{bs}/\rho$, where ρ is a measure for the isolation of the two interfering channels. The assignment of terminals to BSs was swapped when the interference links were stronger than the other links, yielding weak or (unilaterally) strong

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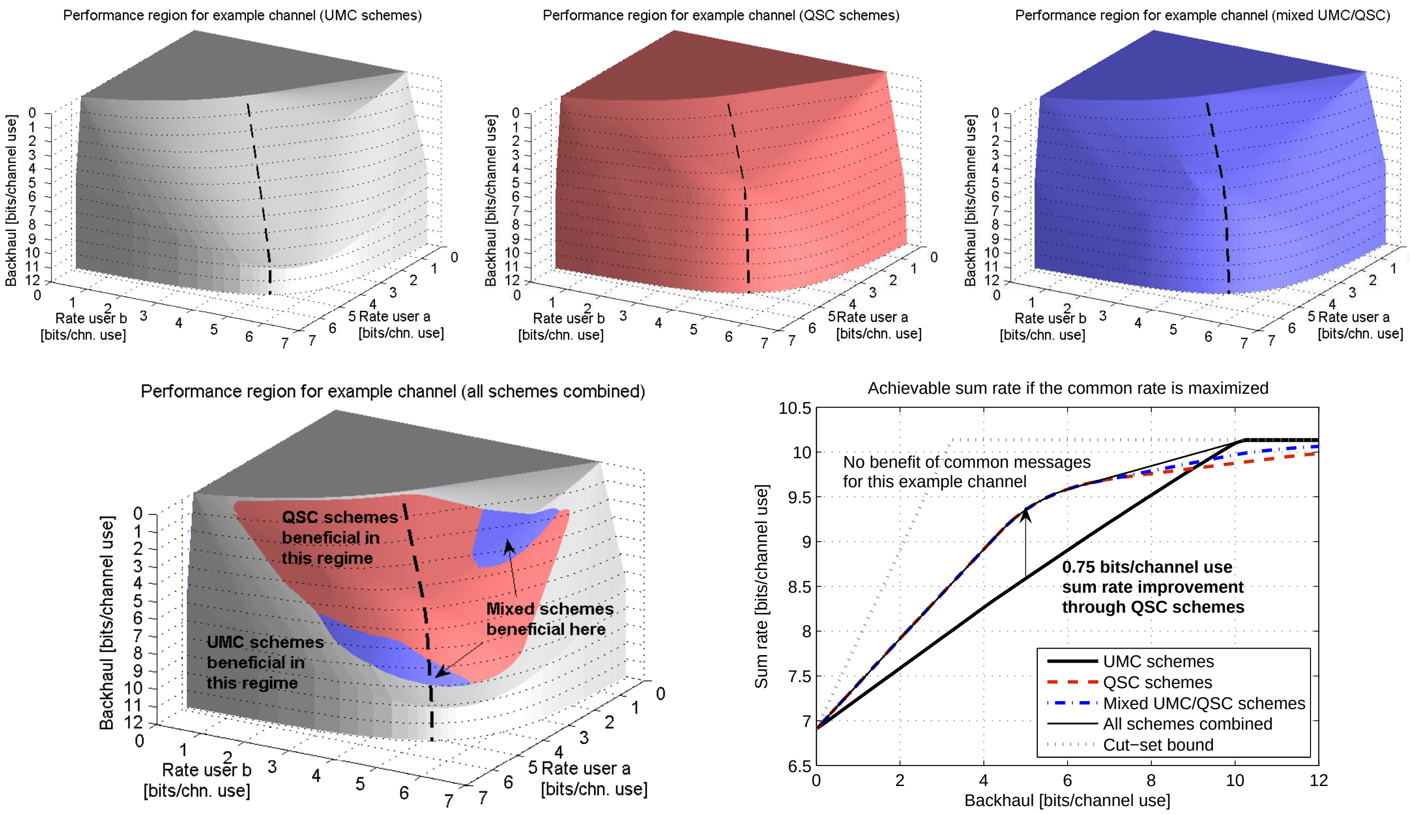

Fig. 2. Performance regions for an example channel and different transmission concepts (dashed line indicates points where common rate is maximized).

interference channels. We plot the average sum rate of both terminals over the required backhaul, if the sum rate itself or the common rate of a, b is maximized. The top plots were obtained under a sum power constraint $P_{max}=2$, the lower plots under a *per-BS* power constraint with $P^A_{max}=P^B_{max}=1$.

As stated before, UMC is always beneficial in and beyond the regime where the backhaul is equal to the maximum sum rate, whereas all schemes asymptotically approach the fully cooperative broadcast channel performance for infinite backhaul. QSC schemes are superior when one BS dominates the system, which is statistically less probable for a larger number of antennas, explaining the poor average performance for $N_{bs} = 2$. Mixed schemes are very suitable to adapt the backhaul usage to asymmetric link conditions, and hence perform equal or better on average than pure UMC or QSC concepts in all observed scenarios. Especially in those cases where the compared schemes perform similar on average, a combined approach (possibly employing time-sharing between the compared schemes) can yield non-negligible gains. The usage of common messages is mainly beneficial in regimes of low backhaul and when optimizing the common rate, as then the rate of one user can be sacrificed to improve that of the other. For $N_{bs} = 2$, local precoding reduces the effective interference, such that the concept of common messages becomes less beneficial, corresponding to observations in [21]. In general, QSC and mixed schemes perform comparatively better than UMC if the terminal rates of the MIMO broadcast channel are large, hence if the spatial separation enabled by the channel is good and background noise is low. Hence, it can be expected that for optimum beamforming schemes QSC and mixed schemes become more attractive.

Our results suggest that for regimes of moderate backhaul, adaptive cooperation schemes appear attractive, while concepts of common messages play a minor role. Omitting the latter would also require the terminals to decode only one message. In practical systems, however, we have to consider that the extent of backhaul required for UMC concepts scales done with the actual throughput (which will be significantly less than the theoretical rates observed here), whereas the backhaul required for QSC will remain the same. As quantization in practical systems will also be subject to more quantization noise than stated through rate distortion theory, one could argue that the usage of only UMC schemes appears most realistic for next generation mobile communications systems.

VII. Conclusions

In this work, we have investigated different forms of base station cooperation in a joint downlink transmission under a constrained backhaul. Results have shown that the trade-off between achievable rates and required backhaul can be improved if the cooperation schemes are combined and adapted to the channel realization. In future work, we plan to do an in-depth

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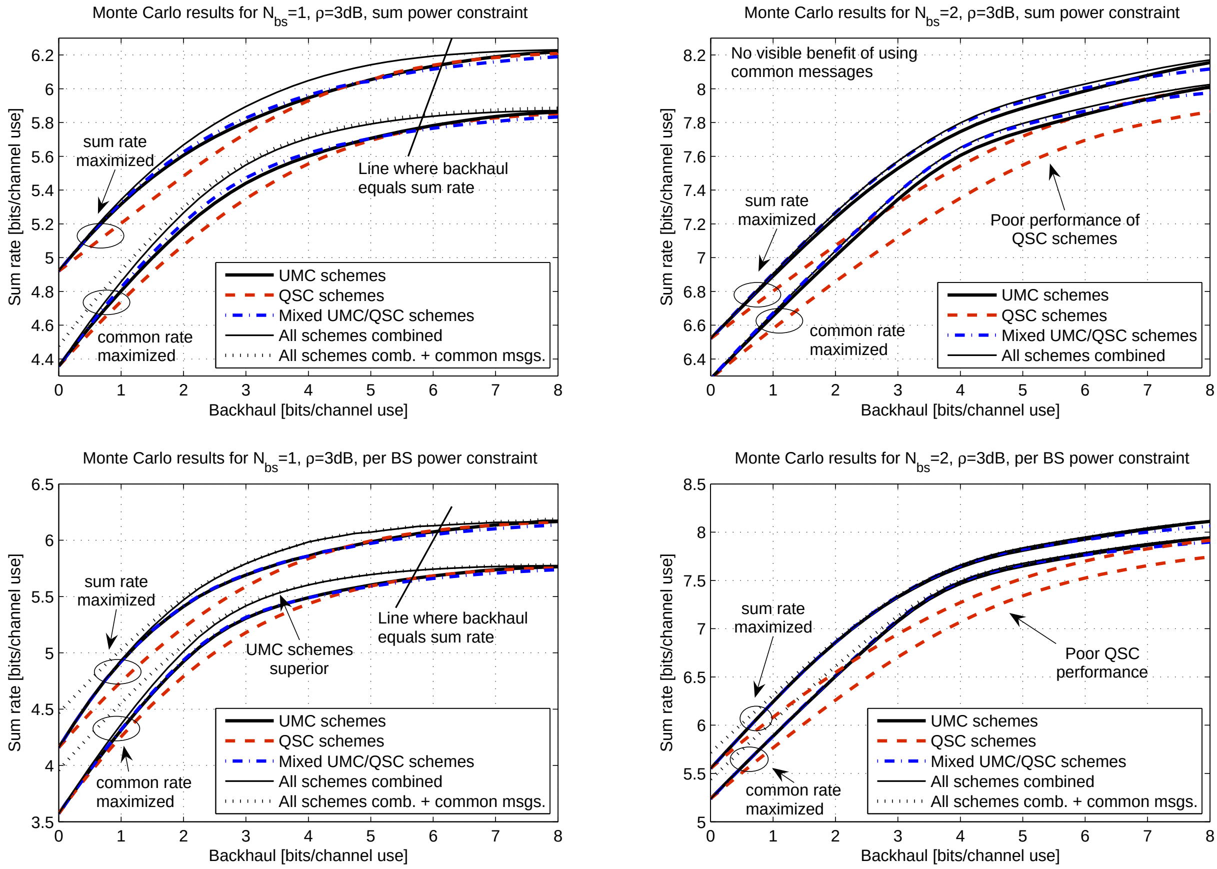

Fig. 3. Monte Carlo simulation results for different numbers of base station antennas N_{bs} and the different cooperation schemes discussed in this paper.

analysis of the channel characteristics for which the different cooperation schemes are beneficial, and determine simple decision criteria according to which a practical system could switch schemes. Further, we want to investigate decentralized QSC schemes where both BSs perform local precoding and provide the other side with quantized signals.

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