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On Backhaul-Constrained Multi-Cell Cooperative Detection based on Superposition Coding

Patrick Marsch, Gerhard Fettweis
Vodafone Chair Mobile Communications Systems
Technische Universität Dresden, Germany
Email: {marsch, fettweis}@ifn.et.tu-dresden.de

***Abstract*— A continuously increasing demand for higher spectral efficiencies in mobile communications will require next generation cellular systems to employ a very dense reuse of spectrum in combination with smart interference mitigation or cancellation schemes. Recent publications have revealed a large potential in terms of spectral efficiency and system fairness of multi-cell cooperative schemes, where e.g. multiple base stations jointly receive or transmit signals connected to multiple terminals. The downside of these schemes is typically the large extent of backhaul link capacity required between base stations. In this paper, we focus on the cellular uplink and investigate the information theoretical limits of multi-cell cooperation under a constrained backhaul. We propose a framework that allows to observe different forms of cooperation between base stations in combination with superposition coding, revealing non-negligible performance improvements compared to our previous results.**

I. Introduction

Multi-cell cooperative signal processing in cellular systems, proposed by e.g. [1], is known to yield strong network capacity and fairness improvements. Assuming an infinite cooperation bandwidth between base stations (BSs), the capacity limits of uplink joint decoding have e.g. been explored in the context of *multiple access channels* by [2], and more realistic bounds for practical OFDMA systems - yet assuming infinite backhaul within large clusters of cooperating BSs - determined in [3].

To make such cooperative schemes attractive for next generation cellular systems, it appears necessary to strongly reduce the extent of backhaul capacity needed between cooperating BSs. We have initially looked into techniques that achieve this by selecting only subsets of terminals for joint signal processing [4], [5] in connection with smart scheduling schemes [6].

In this paper, we investigate information theoretical bounds of backhaul-constrained cooperative decoding in small uplink scenarios. We consider *compress-and-forward* [7] schemes known from cooperative relaying, where the BSs ideally employ Wyner-Ziv coding [8] to enable multi-cell joint decoding at lowest compression noise. Recently, the authors in [9] have combined compress-and-forward techniques based on [10] with the concept that BSs decode parts of the terminals' transmissions themselves, s.t. they need only compress and forward the remaining undecoded signals and noise.

Whereas the work of [9], [11] on backhaul-constrained cooperative decoding is based on a circular Wyner model and the assumption that cooperation takes place through a central unit, we observe arbitrary channel realizations and allow a direct cooperation between BSs, also enabling *decode-and-forward* techniques [7], where the BSs exchange successfully decoded messages for interference subtraction. In [12], we have shown how the performance vs. backhaul tradeoff can be improved through time-sharing between the different cooperation schemes. We now want to investigate possible additional improvements through superposition coding techniques, e.g. by introducing common messages that are decoded by multiple BSs independently, a concept currently known to be the best strategy in non-cooperative *weak interference channels* [13].

The paper is organized as follows. In section II, we describe our system model, basics of cooperative decoding schemes and state achievable rate expressions. In section III, we introduce a mathematical framework for superposition coding enhanced cooperative decoding and formulate an optimization problem in section IV. The paper is concluded with simulation results in section V and conclusions in section VI.

II. System Model

We consider an uplink transmission taking place in a small subset of a cellular mobile communications system. Precisely, we assume that a system scheduler has assigned K terminals (or *UEs*) in $M \leq K$ cells to the same physical resource, such that they observe mutual interference that can be mitigated through multi-cell cooperative decoding. We assume that the transmission sees a frequency-flat channel free of inter-symbol interference (e.g. obtained by transmitting over a single subcarrier of an OFDMA system with a sufficiently designed guard interval), and that all terminals and base stations (BSs) are perfectly synchronized in time and frequency. The terminals are equipped with one transmit antenna each, and the BSs with N_{bs} antennas each, leading to a total of $N_{BS} = MN_{bs}$ receive antennas. The transmission can be stated as

$$\mathbf{y} = \mathbf{H}\mathbf{P}^{\frac{1}{2}}\mathbf{x} + \mathbf{n}, \qquad (1)$$

where $\mathbf{y} \in \mathbb{C}^{[N_{BS}\times 1]}$ are the received signals,

$$\mathbf{H} \in \mathbb{C}^{[N_{BS}\times K]} = [\mathbf{h}_1\mathbf{h}_2 \cdots \mathbf{h}_K] \qquad (2)$$

is a matrix containing the channel coefficients, $\mathbf{P} = \mathrm{diag}(\mathbf{p}) \in \mathbb{R}_0^{+[K\times K]}$ is a matrix with the terminal transmit powers on the diagonal, $\mathbf{x} \in \mathbb{C}^{[K\times 1]}$ are the transmitted signals, assumed to

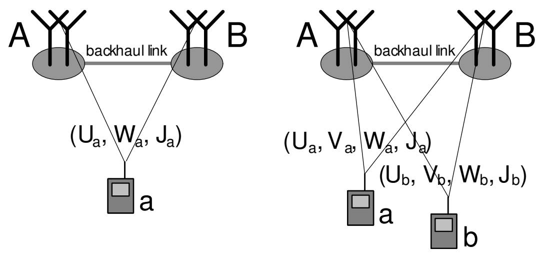

Fig. 1. Example setups with $M=2, K=1$ (left) and $M=K=2$ (right).

be circularly symmetric (c.s.) Gaussian with zero mean and unit variance, and $\mathbf{n} \in \mathbb{C}^{[N_{BS}\times 1]}$ describes AWGN noise at the receive antennas, assumed to be uncorrelated c.s. Gaussian with covariance $E\{\mathbf{n}\mathbf{n}^H\} = \mathbf{\Phi}_{nn}$. We assume that all BSs are connected through an error-free backhaul infrastructure of limited capacity and have perfect knowledge of channel $\mathbf{H}$.

A. Cooperative Detection Schemes

As stated before, we consider direct cooperation between BSs - as opposed to the concept of a central processing unit as in [10], [11]. We consider the following two forms of information exchange between BSs [12]:

1) **Relaying certainty (decode and forward)**. A BS decodes a terminal's signal and forwards the decoded data to other BSs which can then pre-subtract this known interference before decoding other terminals. We call this *distributed interference subtraction* (DIS).
2) **Relaying uncertainty (compress and forward)**. A BS quantizes and forwards received signals to a partnering base station, where (typically) a joint decoding of terminals is performed. This corresponds to a concept often referred to as a *distributed antenna system* (DAS).

In [12] we have seen that a good cooperation strategy for a given channel and backhaul capacity is usually a *time-share* between different DIS/DAS schemes and power allocations. We now want to investigate whether further performance improvements (in terms of achievable rates vs. required backhaul) are possible if BSs can decode *parts* of various transmissions, and thus forward only a smaller portion of decoded data (DIS), or quantize and forward only a smaller remaining uncertainty about received signals (DAS) to other BSs. We model this aspect by combining the DIS and DAS concepts stated before with superposition coding.

B. Achievable Rate Expressions

We state the achievable rate of a transmission m decoded by BS B and interfered by transmissions (or *messages*) $\mathcal{M} = \{m_1, m_2, \cdots, m_{|\mathcal{M}|}\}$ as $R(B, m, \mathcal{M}) =$

$$\mathrm{ld}\left|\mathbf{I} + \left(\mathbf{\Phi}_{nn}^{[B]} + \sum_{m'\in\mathcal{M}} \mathbf{h}_{m'}^{[B]} p_{m'} \mathbf{h}_{m'}^{[B]H}\right)^{-1} \mathbf{h}_m^{[B]} p_m \mathbf{h}_m^{[B]H}\right| \quad (4)$$

where $\mathbf{\Phi}_{nn}^{[B]} \in \mathbb{C}^{[N_{bs}\times N_{bs}]}$ denotes the noise covariance at BS B, and $\mathbf{h}_m^{[B]} \in \mathbb{C}^{[N_{bs}\times 1]}$ denotes the part of channel matrix $\mathbf{H}$ corresponding to the link between the terminal from which message m originates and the antennas of BS B. p_m is the transmit power of message m. If a BS B_1 forwards quantized receive signals to a BS B_2 for joint decoding of a message m, the achievable rate can be stated as in Equation (3), where $\tilde{\mathbf{h}}_m^{[B_2]} \in \mathbb{C}^{[N_{BS}\times 1]}$ is the channel between the terminal transmitting m and *both* BSs, where only the entries associated to BS B_2 are non-zero. Sets $\mathcal{M}_{B_1}$, $\mathcal{M}_{both}$ and $\mathcal{M}_{B_2}$ refer to interfering transmissions as seen by the two BSs, respectively, where $\mathcal{M}_{B_1} \cap \mathcal{M}_{both} = \mathcal{M}_{B_2} \cap \mathcal{M}_{both} = \emptyset$. The first and last set may deviate, for example, if BS B_1 quantizes received signals containing an interferer which, however, has already been decoded by B_2 and can thus be subtracted before the actual joint decoding takes place at B_2. q states the number of quantization bits per channel use, i.e. the backhaul capacity available for cooperation, and the quantization noise is given through rate distortion theory [14] as

$$\mathbf{\Phi}_{qq}(q) = 2^{-\frac{q}{N_{bs}}}\left(\tilde{\mathbf{\Phi}}_{nn}^{[B_1]} + \sum_{m'\in\{\mathcal{M}_{B_1}\cup\ m\}} \tilde{\mathbf{h}}_{m'}^{[B_1]} p_{m'} (\tilde{\mathbf{h}}_{m'}^{[B_1]})^H\right) \quad (5)$$

where $\tilde{\mathbf{\Phi}}_{nn}^{[B_1]} \in \mathbb{C}^{[N_{BS}\times N_{BS}]}$ is equal to the noise covariance $\mathbf{\Phi}_{nn}$, but only elements referring to BS B_1 are non-zero. Eq. (5) implies that quantization can exploit the signal correlation at the N_{bs} antennas of the quantizing BS, but *not* the correlation between multiple BSs. The latter would be possible through e.g. Wyner-Ziv compression [8] which we, however, consider rather unfeasible for practical systems. In our model, we assure that any signal power before quantization is equal to that after quantization plus the quantization noise by using a diagonal scaling matrix $\mathbf{\Xi} \in \mathbb{C}^{[N_{BS}\times N_{BS}]}$, given as

$$\mathbf{\Xi}_{ii}(q) = \begin{cases} 1 - 2^{-q/N_{bs}} & \text{if row } i \text{ in } \mathbf{H} \text{ refers to } B_1 \\ 1 & \text{if row } i \text{ in } \mathbf{H} \text{ refers to } B_2 \\ 0 & \text{otherwise} \end{cases} \quad (6)$$

$$R(B_1 \rightarrow B_2, m, \mathcal{M}_{B_1}, \mathcal{M}_{both}, \mathcal{M}_{B_2}, q) =$$

$$\mathrm{ld}\left|\mathbf{I} + \frac{\overbrace{\mathbf{\Xi}(q)^{\frac{1}{2}}}^{\text{Scaling}} \left(\overbrace{\mathbf{h}_m p_m \mathbf{h}_j^m}^{\text{Covariance of desired signal}}\right) \overbrace{\mathbf{\Xi}(q)^{\frac{1}{2}}}^{\text{Scaling}}}{\underbrace{\mathbf{\Xi}(q)^{\frac{1}{2}}}_{\text{Scaling}} \left(\sum_{m'\in\mathcal{M}_{both}} \mathbf{h}_{m'} p_{m'} \mathbf{h}_{m'}^H + \sum_{m'\in\mathcal{M}_{B_2}} \tilde{\mathbf{h}}_{m'}^{[B_2]} p_{m'} (\tilde{\mathbf{h}}_{m'}^{[B_2]})^H + \mathbf{\Phi}_{nn}\right) \underbrace{\mathbf{\Xi}(q)^{\frac{1}{2}}}_{\text{Scaling}} + \underbrace{\mathbf{\Phi}_{qq}(q)}_{\text{Quant. noise}}}\right| \quad (3)$$

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III. Coop. Detection with Superposition Coding

We now introduce a framework to determine the performance of DIS and DAS schemes with superposition coding.

A. Setup 1: One Terminal

We first consider a setup with $M=2$ and $K=1$, as shown in the left of Fig. 1. We assume the terminal has a stronger link to BS A, and transmits a superposition of messages U_a, W_a and J_a with powers $p_{U_a}+p_{W_a}+p_{J_a}=p_1\leq p_{a,max}$. Message U_a shall be decoded only by BS A, common message W_a decoded by both A and B, and J_a decoded jointly by either BS after cooperation. Obviously, only DAS is possible, and a degree of freedom lies in the direction of cooperation. One could argue that BS A, having the stronger link to the terminal, can locally decode a larger part of the terminal's transmission (via U_a, W_a) and invest the backhaul into compressing only little remaining signal and noise power. To evaluate this, we state the achievable rate of U_a, W_a for a given power allocation as

$$\begin{aligned}R_{U_a,W_a} = \max[&R\left(A,U_a,\{W_a,J_a\}\right)+\\ &\min(R\left(A,W_a,\{J_a\}\right),R\left(B,W_a,\{U_a,J_a\}\right)),\\ &R\left(A,U_a,\{J_a\}\right)+\\ &\min(R\left(A,W_a,\{U_a,J_a\}\right),R\left(B,W_a,\{U_a,J_a\}\right))]\end{aligned} \quad (7)$$

and the overall sum rate as a function of backhaul β_{max} as

$$\begin{aligned}R_a^{[A\to B]} &= R_{U_a,W_a}+R\left(A\to B,J_a,\emptyset,\emptyset,\{U_a\},\beta_{max}\right)\\ R_a^{[B\to A]} &= R_{U_a,W_a}+R\left(B\to A,J_a,\{U_a\},\emptyset,\emptyset,\beta_{max}\right)\end{aligned} \quad (8)$$

for the two directions of signal exchange, respectively. When inserting eq. (3) into eq. (8), it can easily be shown that for any channel, any $\beta_{max}\geq 0$, $\mathbf{\Phi}_{nn}\succeq 0$ and any power allocation between U_a, W_a and J_a, the best cooperation strategy is for the BS with the *weaker* link to forward signals to the other BS. In this case, obviously, the message U_a brings no benefit, and should be assigned zero power.

Fig. 2 shows the performance of the two directions of cooperation vs. the available backhaul β_{max}, and illustrates the strong benefits that are possible through superposition coding for $N_{bs}=1$, $p_{a,max}=1$, $\mathbf{\Phi}_{nn}=0.1\cdot\mathbf{I}$ and an example channel $H=[-0.7952+1.3700i,-0.7644+1.2273i]^T$.

B. Setup 2: Two Terminals

We now consider a setup with $M=K=2$, as shown in the right of Fig. 1. To incorporate both DIS and DAS concepts into our model, we assume that terminals a and b split their transmissions into messages U_a, V_a, W_a, J_a and U_b, V_b, W_b, J_b, respectively, with transmit powers p_{U_a}, p_{U_b} etc., such that

- U_a, U_b are decoded by A, B, respectively, as in [11]
- V_a and V_b are decoded by A and B, respectively, and then forwarded to the other BS (DIS concept)
- W_a and W_b are common messages that are decoded by both BSs, according to the Han Kobayashi scheme [13]
- J_a and J_b are decoded (possibly jointly) by A and B, after an exchange of decoded data (DIS concept) and/or quantized signals (DAS concept) has taken place.

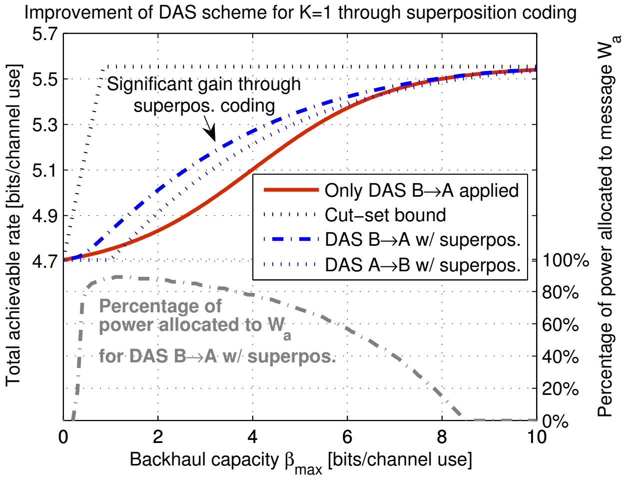

Fig. 2. DAS performance for $K=1$, with or without superposition coding.

We consider only *one* phase of information exchange between the BSs to limit latency. We capture the degree of freedom of the decoding order of the BSs by *ordered* sets

$$\mathcal{M}^{[A]}=\left\{m_1^{[A]}..m_4^{[A]}\right\}=\Pi_A\left\{U_a,V_a,W_a,W_b\right\} \quad (9)$$

$$\mathcal{M}^{[B]}=\left\{m_1^{[B]}..m_4^{[B]}\right\}=\Pi_B\left\{U_b,V_b,W_a,W_b\right\}, \quad (10)$$

where operators Π_X can be arbitrary permutations. We denote the subset of messages that are decoded *after* a message m as

$$\forall X\in\{A,B\},m\in\mathcal{M}^{[X]}:\mathcal{M}_{>m}^{[X]}=\left\{m_{i+1}^{[X]}..m_4^{[X]}\middle|m=m_i^{[X]}\right\}$$

Messages J_a and J_b can be decoded *separately* at both BSs or *jointly* (with SIC) at A or B, denoted through *ordered* sets

$$\begin{aligned}&\bar{\mathcal{M}}^{[A]}\subseteq\{J_a,J_b\},\ \bar{\mathcal{M}}^{[B]}\subseteq\{J_a,J_b\}\\ &\text{s.t. }\bar{\mathcal{M}}^{[A]}\cap\bar{\mathcal{M}}^{[B]}=\emptyset,\ \bar{\mathcal{M}}^{[A]}\cup\bar{\mathcal{M}}^{[B]}=\{J_a,J_b\}\end{aligned} \quad (11)$$

We can now combine all degrees of freedom in a set

$$\mathcal{Z}=\left\{p_{U_a\cdots J_b},\mathcal{M}^{[A]},\mathcal{M}^{[B]},\bar{\mathcal{M}}^{[A]},\bar{\mathcal{M}}^{[B]},q_1,q_2\right\} \quad (12)$$

where q_1,q_2 denote the number of quantization bits used when relaying quantized signals from A to B or vice versa. Using $\mathcal{X}_\mathcal{A}=\{J_a,U_b,V_b,J_b\}$ and $\mathcal{X}_\mathcal{B}=\{U_a,V_a,J_a,J_b\}$, the sum achievable rate of terminal a as a function of $\mathcal{Z}$ is (13)

$$\begin{aligned}R_a\left(\mathcal{Z}\right)=&\underbrace{R\left(A,U_a,\mathcal{M}_{>U_a}^{[A]}\cup\mathcal{X}_\mathcal{A}\right)}_{U_a\text{ decoded by }A}+\underbrace{R\left(A,V_a,\mathcal{M}_{>V_a}^{[A]}\cup\mathcal{X}_\mathcal{A}\right)}_{V_a\text{ dec. by }A\text{ and forw. to }B}\\ &+\min\left(\underbrace{R\left(A,W_a,\mathcal{M}_{>W_a}^{[A]}\cup\mathcal{X}_\mathcal{A}\right)}_{W_a\text{ decoded by }A},\underbrace{R\left(B,W_a,\mathcal{M}_{>W_a}^{[B]}\cup\mathcal{X}_\mathcal{B}\right)}_{W_a\text{ decoded by }B}\right)\\ &+\underbrace{R\left(A\to B,J_a\cap\bar{\mathcal{M}}^{[B]},\{U_b,V_b,J_b\},\bar{\mathcal{M}}_{>J_a}^{[B]}\cup\bar{\mathcal{M}}^{[A]},U_a,q_1\right)}_{J_a\text{ decoded by }B\text{ with DIS/DAS-support from }A}\\ &+\underbrace{R\left(B\to A,J_a\cap\bar{\mathcal{M}}^{[A]},\{U_a,V_a,J_a\},\bar{\mathcal{M}}_{>J_a}^{[A]}\cup\bar{\mathcal{M}}^{[B]},U_b,q_2\right)}_{J_a\text{ decoded by }A\text{ with DIS/DAS-support from }B}\end{aligned}$$

Rate $R_b(\mathcal{Z})$ of terminal b can be derived symmetrically. The backhaul connected to a parameter set $\mathcal{Z}$ is $\beta(\mathcal{Z}) =$

$$q_1 + q_2 + \underbrace{R\left(A, V_a, \mathcal{M}^{[A]}_{>V_a} \cup \mathcal{X}_A\right)}_{V_a \text{ dec. by } A \text{ and forw. to } B} + \underbrace{R\left(B, V_b, \mathcal{M}^{[B]}_{>V_b} \cup \mathcal{X}_B\right)}_{V_b \text{ dec. by } B \text{ and forw. to } A} \quad (14)$$

IV. Performance Regions and Optimization

We define the *performance* connected to a set $\mathcal{Z}$ as $\mathcal{P}(\mathcal{Z}) = \{R_a(\mathcal{Z}), R_b(\mathcal{Z}), \beta(\mathcal{Z})\}$, characterizing both terminal rates and the backhaul required to achieve these rates. We further define all parameter sets that fulfill $p_{U_a} + p_{V_a} + p_{W_a} + p_{J_a} \leq p_{a,max}$, $p_{U_b} + p_{V_b} + p_{W_b} + p_{J_b} \leq p_{b,max}$ as $\mathcal{Z} \in \mathcal{Z}^*$. If we assume that time-sharing between multiple sets of parameters $\mathcal{Z}_1 \cdots \mathcal{Z}_N$ weighted by $|\mathbf{w}| = 1$ is possible, the resulting performance is

$$\tilde{\mathcal{P}}\left(\tilde{\mathcal{Z}} = \{\mathcal{Z}_1, \cdots, \mathcal{Z}_N, \mathbf{w}\}\right) = \sum_{n=1}^{N} w_n \mathcal{P}(\mathcal{Z}_n) \quad (15)$$

As in [12], [15], we define the *achievable performance region* connected to a channel realization and power constraints as the *convex hull* around all performances $\mathcal{P}(\mathcal{Z}), \mathcal{Z} \in \mathcal{Z}^*$ *plus* all points achieving lower rates or requiring more backhaul than any point inside the convex hull, i.e.

$$\mathcal{P}^* = \bigcup_{\substack{\tilde{\mathcal{Z}} = \{\mathcal{Z}_1 \cdots \mathcal{Z}_N, \mathbf{w}\} \\ \mathcal{Z}_i \in \mathcal{Z}^*,\ |\mathbf{w}| = 1}} \left\{ \{R'_a, R'_b, \beta'\} \middle| R'_a \leq \sum_{i=1}^{N} w_i R_a(\mathcal{Z}_i), \right.$$
$$\left. R'_b \leq \sum_{i=1}^{N} w_i R_b(\mathcal{Z}_i),\ \beta' \geq \sum_{i=1}^{N} w_i \beta(\mathcal{Z}_i) \right\} \quad (16)$$

From now on, we assume that an operator wants to maximize the *common* rate of the terminals for a given backhaul β_{max}, s.t. the optimization problem can be stated as

$$\tilde{\mathcal{Z}} = \underset{\substack{\tilde{\mathcal{Z}} = \{\mathcal{Z}_1 \cdots \mathcal{Z}_N, \mathbf{w}\} \\ \mathcal{Z}_i \in \mathcal{Z}^*,\ |\mathbf{w}| = 1}}{\arg\max} \ \min\left(\sum_{i=1}^{N} w_i R_a(\mathcal{Z}_i), \sum_{i=1}^{N} w_i R_a(\mathcal{Z}_i)\right)$$
$$\text{s.t.} \ \sum_{i=1}^{N} w_i \beta(\mathcal{Z}_i) = \beta_{max} \quad (17)$$

V. Simulation Results

It is difficult to approach the topic analytically, as the parameter space from Eq. (12) is large, and the rates in Eq. (13) are non-convex in the power parameters. However, we provide numerical results based on a brute force search through the parameter space to give a deeper insight into the benefit of DIS and DAS schemes and, especially, into that of superposition coding. We compare the following schemes:

- **DIS schemes**. Here, the parameter space is reduced to $\mathcal{Z}^{[DIS]} = \{\mathcal{Z} \in \mathcal{Z}^* | q_1 = q_2 = 0\}$, hence the backhaul is only invested into exchanging already decoded messages.
- **DAS schemes**. Here, the parameter space is reduced to $\mathcal{Z}^{[DAS]} = \{\mathcal{Z} \in \mathcal{Z}^* | p_{V_a} = p_{V_b} = 0\}$, hence the backhaul is only invested into exchanging quantized signals.
- **DIS/DAS combined**, with the full parameter space $\mathcal{Z}^*$.

In general, where superposition coding is not explicitly stated, the transmit power of each terminal is only invested into *one* of the possible messages. Note that DIS and DAS refer only to the way the backhaul is used; in both cases messages J_a, J_b can be decoded separately by both BSs or jointly by one. In this section, we provide results for $M = K = 1$ and $N_{bs} = 1$ and observe channels that are normalized to

$$\mathbf{H} = \begin{bmatrix} 1 & \sqrt{\lambda_{Ab}} e^{-j\phi_{Ab}} \\ \sqrt{\lambda_{Ba}} e^{-j\phi_{Ba}} & 1 \end{bmatrix} \quad (18)$$

We define $-1 \leq \theta = \text{Re}\{e^{j\phi_{Ba}} e^{j\phi_{Ab}}\} \leq 1$, which is an indicator for the orthogonality defect of the channel, i.e. a smaller θ means that the terminals can be better spatially separated if DAS concepts are used. This allows to capture all aspects relevant for rate and backhaul computation in the parameters λ_{Ab}, λ_{Ba}, θ, $p_{a,max}$, $p_{b,max}$ and $\mathbf{\Phi}_{nn}$.

The top left plot in Fig. 3 shows whether DIS or DAS concepts yield a superior common rate, for a fixed $\beta_{max} = 2$ bits/channel use, $\theta = -0.3$, $p_{a,max} = p_{b,max} = 1$ and $\mathbf{\Phi}_{nn} = 0.1 \cdot \mathbf{I}$. As for $K = 1$, DAS schemes perform best if the *weaker* BS forwards quantized signals to the *stronger* BS. Only for very weak interference ($\lambda_{Ab}, \lambda_{Ba} \lesssim -10dB$), hence where thermal noise dominates interference, using DAS in both directions simultaneously with separate decoding is better. The same applies to the very strong interference case, if the BS-terminal assignment is swapped. DIS schemes are superior for $\lambda_{Ab}[dB] + \lambda_{Ba}[dB] \lesssim -10dB$, or for very strong interference and again a swapped BS-terminal assignment.

The lower two plots compare the performance of the discussed schemes along two trajectories of values for $\lambda_{Ab}, \lambda_{Ba}$ that we consider within a region of interest. In the left case, we can again see the superiority of DIS or bi-directional DAS schemes for $\lambda_{Ab} = \lambda_{Ba} \lesssim -5dB$. Superposition coding appears marginally beneficial for $-12dB \lesssim \lambda_{Ab} = \lambda_{Ba} \lesssim -7dB$. The right case, however, shows that superposition coding becomes more beneficial in assymetrical interference cases.

The upper right plot shows an example channel where superposition coding is highly beneficial. Here, $\lambda_{Ab} = -7dB$, $\lambda_{Ba} = -14dB$, the other parameters are as above, and the sum rate for an optimized common rate is plotted over the backhaul. For a sum rate of 6 bits/channel use, this yields a 15% decrease in backhaul compared to a standard DIS, or 32% reduction compared to DAS. In this example, superposition coding is already beneficial for zero backhaul, due to the concept of common messages (Han-Kobayashi [13]).

In general, the gains of superposition coding appear to diminish when the system size (M, K) is increased. This is quite intuitive, as then the benefit of common messages (i.e. to sacrifice the rate of one user to improve the rate of another or to make signal compression more efficient) disappears in an increased background interference and noise floor. For most channels, a simultaneous usage of DIS and DAS concepts through superposition coding appears to yield only marginal gain over a simple time-share between DIS and DAS, while being far more complicated to implement in practise.

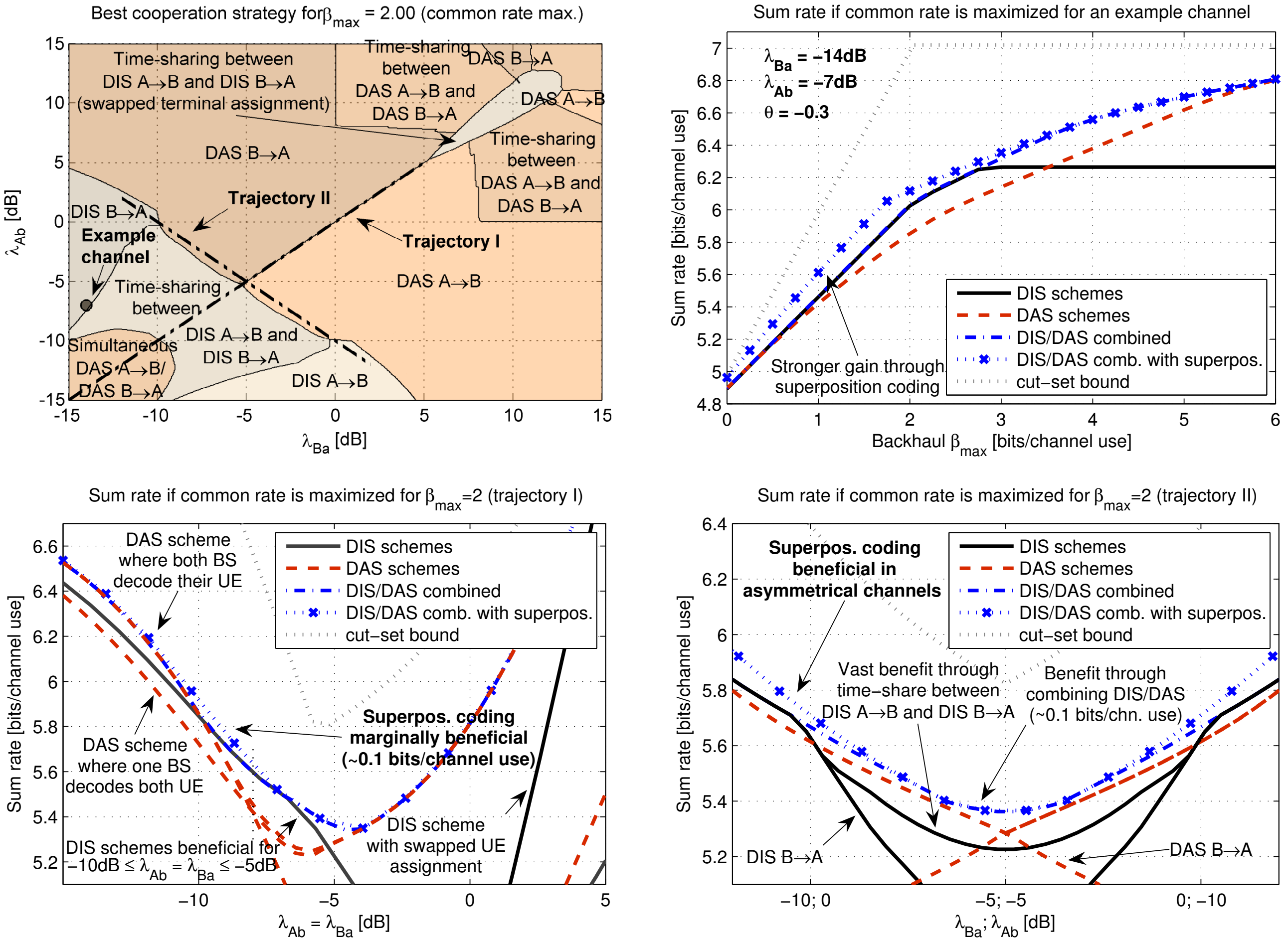

Fig. 3. Numerical results for the performance of the observed DIS and DAS approaches with and without superposition coding

VI. Conclusions

We have derived a framework to observe the performance of multi-cell joint decoding schemes in combination with superposition coding. Simulation has shown that superposition coding does improve performance for some channels, but that combinations of the basic cooperation schemes without superposition coding already perform substantially well while appearing more feasible for practical systems. Further research is necessary on a complete characterization of the channel conditions under which superposition coding is most beneficial.

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