

A superposition scheme for downlink multicell processing with finite backhaul capacity

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Abstract: In the scenario of downlink multicell processing with finite backhaul capacity in the case of two base stations and two mobile users, by regarding the channel as a multiple access diamond channel with two destinations, an achievability scheme that sends correlated codewords through the multiple access channel with common data is proposed. By considering the superposition structure, fully correlated codewords can be supported by the proposed scheme, which can benefit the system throughput in the case of a relatively-large-capacity backhaul. First, an achievable region for the achievable theory is given and it is proved from the perspective of information theory. Then, in the Gaussian scenario, a simulation combining dirty-paper coding and power allocating is provided for the achievable region. Simulation results demonstrate that when the backhaul capacity is relatively large, the proposed scheme outperforms the existing achievability scheme without the superposition structure.

Key words: multicell processing; finite backhaul capacity; superposition; dirty-paper coding; power allocating

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In cellular networks, multicell processing is a promising technique that allows for the joint processing of different base stations' (BSs') signals for the downlink or uplink, which increases the throughput of cellular systems^[1-2]. Traditionally, in the scenario of downlink multicell processing, the experiment has been carried out under the assumption that all the base stations in the network obtain the data for all users via unlimited capacity links between the BSs and the central processor (CP)^[3]. In this case, the cellular network forms a distributed MIMO broadcast channel which can improve the system throughput greatly^[4]. However, the BSs communicate with the CP via finite-capacity backhaul in many practical scenarios^[5]. The limited capacity backhaul links may not always suffice for the transmitting of the data of all the users

from the CP to all the BSs, and as a result, the limited capacity backhaul links may become a bottleneck of network throughput. Therefore, it is interesting to investigate how to make the best use of finite-capacity backhaul links.

Several achievability schemes have been proposed for downlink multicell processing with finite-capacity backhaul. Ref. [6] proposed a compressed dirty-paper coding (DPC) scheme, where signals are precoded and compressed in the CP and then transmitted to the BSs. Improvements on this scheme were made in Ref. [7] by considering multivariate compression to introduce correlation between the quantization noises. A data sharing scheme was proposed in Ref. [8], where the message for each user from the CP is split into two types, consisting of private data intended for a single BS and common data intended for all BSs. In Ref. [9], a hybrid strategy combining the compression and data-sharing strategies was proposed, where messages for some users are sent directly to the BSs using part of the backhaul capacity while messages for the remaining users are precoded and compressed before being transmitted to the BSs using the rest of the backhaul capacity. A reverse compute-and-forward (RCoF) scheme was proposed in Ref. [10], where the limited backhaul is used to transmit the linear combinations of the precoded messages over a finite field. The achievability scheme proposed in Ref. [11] combines Marton's achievability for the broadcast channel^[12] and the achievability of sending correlated codewords over a multiple access channel^[13]. The CP transmits the index information of correlated codewords to BSs via the finite-capacity backhaul link. Numerical results show that this scheme outperforms schemes proposed in Refs. [7, 10] in certain cases.

In this paper, aiming at studying the two-cell downlink multicell processing problem, enlightened by the achievability scheme in Refs. [14 – 15], an achievability scheme was proposed, which is similar to the achievability scheme in Ref. [11], except that superposition coding is introduced. Ref. [14] shows that the achievability scheme with superposition outperforms the achievability scheme without superposition when the backhaul capacity is relatively large, since the superposition scheme can fully support correlated codewords while the non-superposition scheme cannot. Technically, similar to Ref. [11],

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by treating the problem as a Gaussian multiple access diamond channel with two destinations, our scheme can be viewed as the extension of the achievability scheme in Ref. [14]. More specifically, an inner codebook containing parts of the messages decoded by both BSs is introduced, which serves as common data. Four outer codebooks are then generated, two of which correspond to the remaining part of the message and two that correspond to two BSs. The BSs send correlated codewords along with the common data into the multiple access channel with two destinations. Since the superiority of the achievability scheme in Ref. [11] over other existing schemes for certain cases lies in its exploiting the gain of correlation between the transmitted signals from the BSs, our achievability scheme outperforms that of Ref. [11] when the backhaul link capacity is relatively large, due to the fact that with the introduction of superposition coding, more correlation between the transmitted signals from two BSs are supported. This is demonstrated through numerical results.

1 System Model

The following channel model is considered, which is named the two-destination multiple access diamond channel^[4]. The capacity link from the CP to BS k is C_k , $k = 1, 2$. The channel between the two BSs and the two mobile users (MUs) is characterized by $p(y_1, y_2 | x_1, x_2)$ with input alphabets (X_1, X_2) and output alphabets (Y_1, Y_2) . The system model is depicted in Fig. 1.

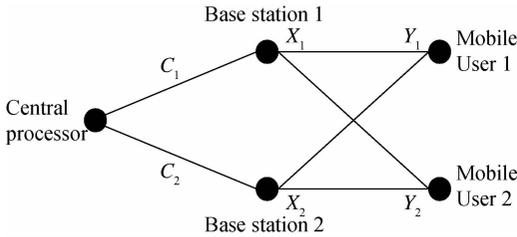


Fig. 1 The multicell processing model with two cells and two users

Let W_1 and W_2 be two independent messages transmitted from the CP to MU1 and MU2, respectively. Assume that W_k is uniformly distributed on $\{1, 2, \dots, M_k\}$, $k = 1, 2$. An $(M_1, M_2, n, \varepsilon_n)$ code consists of an encoding function at the CP $f^n: \{1, 2, \dots, M_1\} \times \{1, 2, \dots, M_2\} \rightarrow \{1, 2, \dots, 2^{nC_1}\} \times \{1, 2, \dots, 2^{nC_2}\}$, two encoding functions at the two BSs $f_k^n: \{1, 2, \dots, 2^{nC_k}\} \rightarrow X_k^n$, $k = 1, 2$, and two decoding functions at the MUs $g_k^n: Y_k^n \rightarrow \{1, 2, \dots, M_k\}$, $k = 1, 2$. The average probability of error is defined as

$$\varepsilon_n = \sum_{w_1=1}^{M_1} \sum_{w_2=1}^{M_2} \frac{1}{M_1 M_2}$$

$$\Pr\{g_1^n(Y_1^n) \neq w_1 \text{ or } g_2^n(Y_2^n) \neq w_2 \mid W_1 = w_1, W_2 = w_2\}$$

Rate pair (R_1, R_2) is said to be achievable if there is a

sequence of $(2^{nR_1}, 2^{nR_2}, n, \varepsilon_n)$ codes such that $\varepsilon_n \rightarrow 0$ as $n \rightarrow \infty$. The capacity region of the two-destination multiple access diamond channel is the closure of the set of all rate pairs.

For the two-destination Gaussian multiple access diamond channel, $X_1 = X_2 = Y_1 = Y_2 = R$ and the channel between the two BSs and each MU is a Gaussian multiple access channel. Thus, the received signal at the MUs are

$$Y_1 = X_1 + aX_2 + Z_1 \quad (1)$$

$$Y_2 = bX_1 + X_2 + Z_2 \quad (2)$$

where X_1 and X_2 are the input signals from BSs 1 and 2, respectively, and Z_1, Z_2 are two independent zero-mean unit-variance Gaussian random variables. It is assumed that (Z_1, Z_2) is independent of (X_1, X_2) . The encoding functions at the two BSs must satisfy the average power constraints. For any x_k^n that BS k sends to the Gaussian multiple access channel, it satisfies

$$\frac{1}{n} \sum_{i=1}^n x_{ki}^2 \leq P_k \quad k = 1, 2$$

2 Achievability for Two-Destination Multiple Access Diamond Channel

Theorem 1 is the main result of this paper, which provides an achievable region for the two-destination multiple access diamond channel. By introducing the superposition structure, an inner codebook of correlated codewords is generated and the message index of this codebook is transmitted to both BSs. As a result, it forms common data at the two BSs, and they can beamform the common data to both receivers.

Theorem 1 Rate pair (R_1, R_2) is achievable for the two-destination multiple access diamond channel $p(y_1, y_2 | x_1, x_2)$ with parameters C_1, C_2, Q_{10}, Q_{20} if it satisfies

$$R_1 \leq I(U_0, U_1, U_2; Y_1) - I(U_1, U_2; V_0 | U_0) \quad (3)$$

$$R_1 \leq I(U_1, U_2; Y_1 | U_0) + Q_{10} - I(U_1, U_2; V_0 | U_0) \quad (4)$$

$$R_1 \leq C_1 + I(U_1; V_0 | U_0) + I(V_1; U_0 | V_0) + I(U_1; V_1 | U_0, V_0) + I(U_2; Y_1 | U_1, U_0) - I(U_1, U_2; V_0 | U_0) - Q_{20} \quad (5)$$

$$R_1 \leq C_2 + I(U_2; V_0 | U_0) + I(V_2; U_0 | V_0) + I(U_2; V_2 | U_0, V_0) + I(U_1; Y_1 | U_2, U_0) - I(U_1, U_2; V_0 | U_0) - Q_{20} \quad (6)$$

$$R_2 \leq I(V_0, V_1, V_2; Y_2) - I(V_1, V_2; U_0 | V_0) \quad (7)$$

$$R_2 \leq I(V_1, V_2; Y_2 | V_0) + Q_{20} - I(V_1, V_2; U_0 | V_0) \quad (8)$$

$$R_2 \leq C_1 + I(U_1; V_0 | U_0) + I(V_1; U_0 | V_0) + I(U_1; V_1 | U_0, V_0) + I(V_2; Y_2 | V_1, U_0) - I(V_1, V_2; U_0 | V_0) - Q_{10} \quad (9)$$

$$R_2 \leq C_2 + I(U_2; V_0 | U_0) + I(V_2; U_0 | V_0) + I(U_2; V_2 | U_0, V_0) + I(V_1; Y_2 | V_2, U_0) - I(V_1, V_2; U_0 | V_0) - Q_{10} \quad (10)$$

$$R_1 + R_2 \leq I(U_0, U_1, U_2; Y_1) + I(V_0, V_1, V_2; Y_2) - I(U_1, U_2; V_0 | U_0) - I(V_1, V_2; U_0 | V_0) -$$

$$I(U_1, U_2; V_1, V_2 | U_0, V_0) - I(U_0; V_0) \quad (11)$$

$$R_1 + R_2 \leq I(U_1, U_2; Y_1 | U_0) + Q_{10} + I(V_0, V_1, V_2; Y_2) - I(U_1, U_2; V_0 | U_0) - I(V_1, V_2; U_0 | V_0) - I(U_1, U_2; V_1, V_2 | U_0, V_0) \quad (12)$$

$$R_1 + R_2 \leq I(U_0, U_1, U_2; Y_1) + I(V_1, V_2; Y_2 | V_0) + Q_{20} - I(U_1, U_2; V_0 | U_0) - I(V_1, V_2; U_0 | V_0) - I(U_1, U_2; V_1, V_2 | U_0, V_0) \quad (13)$$

$$R_1 + R_2 \leq I(U_1, U_2; Y_1 | U_0) + Q_{10} + I(V_1, V_2; Y_2 | V_0) + Q_{20} - I(U_1, U_2; V_0 | U_0) - I(V_1, V_2; U_0 | V_0) - I(U_1, U_2; V_1, V_2 | U_0, V_0) \quad (14)$$

$$R_1 + R_2 \leq C_1 + I(U_1; V_0 | U_0) + I(V_1; U_0 | V_0) + I(U_1; V_1 | U_0, V_0) + I(U_2; Y_1 | U_1, U_0) + I(V_2; Y_2 | V_1, V_0) - I(U_1, U_2; V_0 | U_0) - I(V_1, V_2; U_0 | V_0) - I(U_1, U_2; V_1, V_2 | U_0, V_0) \quad (15)$$

$$R_1 + R_2 \leq C_2 + I(U_2; V_0 | U_0) + I(V_2; U_0 | V_0) + I(U_2; V_2 | U_0, V_0) + I(U_1; Y_1 | U_2, U_0) + I(V_1; Y_2 | V_2, V_0) - I(U_1, U_2; V_0 | U_0) - I(V_1, V_2; U_0 | V_0) - I(U_1, U_2; V_1, V_2 | U_0, V_0) \quad (16)$$

$$R_1 + R_2 \leq C_1 + I(U_1; V_0 | U_0) + I(V_1; U_0 | V_0) + I(U_1; V_1 | U_0, V_0) + C_2 + I(U_2; V_0 | U_0) + I(V_2; U_0 | V_0) + I(U_2; V_2 | U_0, V_0) - I(U_1; U_2 | U_0) - I(V_1; V_2 | V_0) - I(U_1, U_2; V_0 | U_0) - I(V_1, V_2; U_0 | V_0) - I(U_1, U_2; V_1, V_2 | U_0, V_0) - Q_{10} - Q_{20} \quad (17)$$

$$I(U_1; V_0 | U_0) + I(V_1; U_0 | V_0) + I(U_1; V_1 | U_0, V_0) \leq I(U_1; Y_1, U_2 | U_0) + I(V_1; Y_2, V_2 | U_0) \quad (18)$$

$$I(U_2; V_0 | U_0) + I(V_2; U_0 | V_0) + I(U_2; V_2 | U_0, V_0) \leq I(U_2; Y_1, U_1 | U_0) + I(V_2; Y_2, V_1 | U_0) \quad (19)$$

for some distribution $p(u_0, u_1, u_2, v_0, v_1, v_2)p(x_1 | u_0, u_1, v_0, v_1)p(x_2 | u_0, u_2, v_0, v_2)$, and some Q_{10} and Q_{20} that satisfy $(Q_{10} + Q_{20}) \leq \min\{C_1, C_2\}$ and $Q_{k0} \geq 0$, $k = 1, 2$.

A brief outline of the proof of Theorem 1 is as follows: The CP uses a codebook of the superposition structure, where $(Q_{10} + Q_{20})$ is the rate of the inner codebook. More specifically, for $k = 1, 2$, the CP splits message M_k into three parts, i. e., M_{k0} with rate Q_{k0} , M_{k1} with rate $(R_{k1} - r_{k1})$ and M_{k2} with rate $(R_{k2} - r_{k2})$. The CP encodes M_{10} and M_{20} into the inner codebook of correlated codewords, and delivers the corresponding codeword index to both BSs. Then, the CP encodes the remaining parts of the two messages into four outer codebooks.

The CP encodes M_{k1} and M_{k2} into an outer codebook, which contains correlated codeword pairs, $k = 1, 2$. This codebook along with the inner codebook will be used by MU k in decoding M_{k0} , M_{k1} , M_{k2} .

The CP encodes M_{1k} and M_{2k} into another outer codebooks containing correlated codeword pairs, $k = 1, 2$. This codebook along with the inner codebook will be used by BS k to find the corresponding codeword x_k^n to be sent to the multiple access channel with two destinations, $k =$

1, 2.

The details of the proof of Theorem 1 are provided as follows. Based on a given distribution, the proof consists of four basic steps named codebook generation, encoding, decoding, and probability of error analysis.

A distribution $p(u_0, u_1, u_2, v_0, v_1, v_2)p(x_1 | u_0, u_1, v_0, v_1)p(x_2 | u_0, u_2, v_0, v_2)$ is fixed and the following proof will be based on this distribution.

The first part of the proof is codebook generation. Generate $2^{n(R_{10} - r_{10})}$ codebooks $C_{U_0}(i_0)$, each consisting of $2^{nr_{10}}$ u_0^n sequences, in an i. i. d. fashion according to $p(u_0)$, where $i_0 \in [1: 2^{n(R_{10} - r_{10})}]$. Index each codeword as $u_0^n(i_0, l_0)$, where $l_0 \in [1: 2^{nr_{10}}]$. Similarly, generate $2^{n(R_{20} - r_{20})}$ codebooks $C_{V_0}(j_0)$, each consisting of $2^{nr_{20}}$ v_0^n sequences, in an i. i. d. fashion according to $p(v_0)$, where $j_0 \in [1: 2^{n(R_{20} - r_{20})}]$. Index each codeword as $v_0^n(j_0, m_0)$, where $m_0 \in [1: 2^{nr_{20}}]$. Let

$$Q_{k0} = R_{k0} - r_{k0} \quad k = 1, 2 \quad (20)$$

For each $u_0^n(i_0, l_0)$ sequence where $i_0 \in [1: 2^{nQ_{10}}]$, $l_0 \in [1: 2^{nr_{10}}]$, generate $2^{n(R_{11} - r_{11})}$ codebooks $C_{U_1|U_0}(i_0, l_0, i_k)$ for $k = 1, 2$, each consisting of $2^{nr_{1k}}$ u_k^n sequences, in a conditional i. i. d. fashion according to $p(u_k | u_0)$, where $i_k \in [1: 2^{n(R_{1k} - r_{1k})}]$. Label these u_k^n sequences as $u_k^n(i_0, l_0, i_k)$, $i_k \in [(i_k - 1)2^{nr_{1k}}; i_k 2^{nr_{1k}}]$. Furthermore, for each (i_0, l_0, i_1, i_2) , find all codeword pairs (u_1^n, u_2^n) that are jointly typical conditioned on $u_0^n(i_0, l_0)$ according to $p(u_1, u_2 | u_0)$, where $u_1^n \in C_{U_1|U_0}(i_0, l_0, i_1)$ and $u_2^n \in C_{U_2|U_0}(i_0, l_0, i_2)$. The set of all codeword pairs found is denoted as $C_{U_1, U_2|U_0}(i_0, l_0, i_1, i_2)$. According to Ref. [15], the number of such codeword pairs is lower bounded by $2^{n(r_{11} + r_{12} - I(U_1, U_2|U_0))}$.

Similarly, for each $v_0^n(j_0, m_0)$ sequence where $j_0 \in [1: 2^{nQ_{20}}]$, $m_0 \in [1: 2^{nr_{20}}]$, generates $2^{n(R_{21} - r_{21})}$ codebooks $C_{V_1|V_0}(j_0, m_0, j_k)$ for $k = 1, 2$, each consisting of $2^{nr_{2k}}$ v_k^n sequences, in a conditional i. i. d. fashion according to $p(v_k | v_0)$, where $j_k \in [1: 2^{n(R_{2k} - r_{2k})}]$. Label these v_k^n sequences as $v_k^n(j_0, m_0, j_k)$, $j_k \in [(j_k - 1)2^{nr_{2k}}; j_k 2^{nr_{2k}}]$. Furthermore, for each (j_0, m_0, j_1, j_2) , find all codeword pairs (v_1^n, v_2^n) that are jointly typical conditioned on $v_0^n(j_0, m_0)$ according to $p(v_1, v_2 | v_0)$, where $v_1^n \in C_{V_1|V_0}(j_0, m_0, j_1)$ and $v_2^n \in C_{V_2|V_0}(j_0, m_0, j_2)$. The set of all codeword pairs found is denoted as $C_{V_1, V_2|V_0}(j_0, m_0, j_1, j_2)$. According to Ref. [15], the number of such codeword pairs is lower bounded by $2^{n(r_{21} + r_{22} - I(V_1, V_2|V_0))}$.

For each pair (i_0, j_0) , find a jointly typical sequence pair (u_0^n, v_0^n) according to $p(u_0, v_0)$, where $u_0^n \in C_{U_0}(i_0)$ and $v_0^n \in C_{V_0}(j_0)$. According to mutual covering lemma in Ref. [1], there exists such a jointly typical pair if

$$r_{10} + r_{20} \geq I(U_0; V_0) \quad (21)$$

If there are such multiple codeword pairs, pick one pair randomly, and then label the codeword pair found as $(u_0^n$

$(i_0, \hat{l}_0(i_0, j_0)), v_0^n(j_0, \hat{m}_0(i_0, j_0))$. Consequently, $2^{n(Q_{10} + Q_{20})}$ such (u_0^n, v_0^n) pairs which form the inner codebook $C_{U_0 V_0}$ are obtained.

For each $(i_0, j_0, i_1, i_2, j_1, j_2)$, where $i_0 \in [1:2^{nQ_{10}}]$, $j_0 \in [1:2^{nQ_{20}}]$, $i_k \in [1:2^{n(R_{1k} - r_{1k})}]$, $j_k \in [1:2^{n(R_{2k} - r_{2k})}]$, $k = 1, 2$, the following steps are performed:

Step 1 Find all codeword pairs $(u_1^n, u_2^n) \in C_{U_1, U_2 | U_0}$ $(i_0, \hat{l}_0(i_0, j_0), i_1, i_2)$ that are jointly typical with $v_0^n(j_0, \hat{m}_0(i_0, j_0))$ conditioned on $u_0^n(i_0, \hat{l}_0(i_0, j_0))$ according to $p(u_1, u_2, v_0 | u_0)$. The set of such codeword pairs is denoted as $C_{U_1, U_2 | U_0, V_0}(i_0, j_0, i_1, i_2)$. According to Ref. [15], the number of such codeword pairs is lower bounded by 2^{nr_1} , where

$$r_1 = r_{11} + r_{12} - I(U_1; U_2 | U_0) - I(U_1, U_2; V_0 | U_0) \quad (22)$$

Note that it requires $r_1 > 0$.

Step 2 Find all codeword pairs $(v_1^n, v_2^n) \in C_{V_1, V_2 | V_0}(j_0, \hat{m}_0(i_0, j_0), j_1, j_2)$ that are jointly typical with $u_0^n(i_0, \hat{l}_0(i_0, j_0))$ conditioned on $v_0^n(j_0, \hat{m}_0(i_0, j_0))$ according to $p(v_1, v_2, u_0 | v_0)$. The set of such codeword pairs is denoted as $C_{V_1, V_2 | U_0, V_0}(i_0, j_0, j_1, j_2)$. According to Ref. [15], the number of such codeword pairs is lower bounded by 2^{nr_2} , where

$$r_2 = r_{21} + r_{22} - I(V_1; V_2 | V_0) - I(V_1, V_2; U_0 | V_0) \quad (23)$$

Note that it requires $r_2 > 0$.

Step 3 For $k = 1, 2$, find all codewords $u_k^n \in C_{U_k | U_0}$ $(i_0, \hat{l}_0(i_0, j_0), i_k)$ that are jointly typical with $v_0^n(j_0, \hat{m}_0(i_0, j_0))$ conditioned on $u_0^n(i_0, \hat{l}_0(i_0, j_0))$ according to $p(u_k, v_0 | u_0)$. The set of such codewords is denoted as $C_{U_k | U_0, V_0}(i_0, j_0, i_k)$. Similarly, find all codewords $v_k^n \in C_{V_k | V_0}(j_0, \hat{m}_0(i_0, j_0), j_k)$ that are jointly typical with $u_0^n(i_0, \hat{l}_0(i_0, j_0))$ conditioned on $v_0^n(j_0, \hat{m}_0(i_0, j_0))$ according to $p(v_k, u_0 | v_0)$. The set of such codewords is denoted as $C_{V_k | U_0, V_0}(i_0, j_0, j_k)$. Furthermore, find all codeword pairs (u_k^n, v_k^n) that are jointly typical conditioned on $(u_0^n(i_0, \hat{l}_0(i_0, j_0)), v_0^n(j_0, \hat{m}_0(i_0, j_0)))$ according to $p(u_k, v_k | u_0, v_0)$, where $u_k^n \in C_{U_k | U_0, V_0}(i_0, j_0, i_k)$, $v_k^n \in C_{V_k | U_0, V_0}(i_0, j_0, j_k)$. Denote such codeword pairs found as $C_{U_k, V_k | U_0, V_0}(i_0, j_0, i_k, j_k)$. According to [15], the number of codeword pairs in $C_{U_k, V_k | U_0, V_0}(i_0, j_0, i_k, j_k)$ is upper bounded by $2^{n(r_{UVk} + \epsilon)}$, where

$$r_{UVk} = r_{1k} - I(U_k; V_0 | U_0) + r_{2k} - I(V_k; U_0 | V_0) - I(U_k; V_k | U_0, V_0) \quad (24)$$

It also requires $r_{UVk} \geq 0$, for $k = 1, 2$.

Step 4 For $k = 1, 2$, for each codeword pair (u_k^n, v_k^n) in $C_{U_k, V_k | U_0, V_0}(i_0, j_0, i_k, j_k)$, generate an x_k^n sequence in a conditional i. i. d. fashion according to the distribution $p(x_k | u_k, v_k, u_0, v_0)$.

Now, we describe the encoding procedure. At the cen-

tral processor, message W_k ($k = 1, 2$) is split into (W_{ka}, W_{kb}, W_{kc}) , where W_{ka} , W_{kb} and W_{kc} are uniformly distributed on $\{1, 2, \dots, 2^{nQ_{1a}}\}$, $\{1, 2, \dots, 2^{n(R_{1a} - r_{1a})}\}$ and $\{1, 2, \dots, 2^{n(R_{1a} - r_{1a})}\}$, respectively. When

$$(W_{ka}, W_{kb}, W_{kc}) = (w_{ka}, w_{kb}, w_{kc}) \quad k = 1, 2$$

the central processor inspects $C_{U_1, U_2 | U_0, V_0}(w_{1a}, w_{2a}, w_{1b}, w_{1c})$ and $C_{V_1, V_2 | U_0, V_0}(w_{1a}, w_{2a}, w_{2b}, w_{2c})$ for a codeword quadruple $(u_1^n, u_2^n, v_1^n, v_2^n)$ that are jointly typical conditioned on $(u_0^n(w_{1a}, \hat{l}_0(w_{1a}, w_{2a})), v_0^n(w_{2a}, \hat{m}_0(w_{1a}, w_{2a})))$ according to the distribution $p(u_1, u_2, v_1, v_2 | u_0, v_0)$. Let the found quadruple be denoted by $(\bar{u}_1^n, \bar{u}_2^n, \bar{v}_1^n, \bar{v}_2^n)$. If no such quadruple can be found, the central processor sends 1 to both BSs 1 and 2.

Since joint typicality implies marginal typicality, $(\bar{u}_1^n, \bar{v}_1^n)$ is in codebook $C_{U_1, V_1 | U_0, V_0}(w_{1a}, w_{2a}, w_{1b}, w_{2b})$, and similarly, $(\bar{u}_2^n, \bar{v}_2^n)$ is in codebook $C_{U_2, V_2 | U_0, V_0}(w_{1a}, w_{2a}, w_{1c}, w_{2c})$. The central processor sends $(w_{1a}, w_{2a}, w_{1b}, w_{2b})$ and the row index of $(\bar{u}_1^n, \bar{v}_1^n)$ in $C_{U_1, V_1 | U_0, V_0}(w_{1a}, w_{2a}, w_{1b}, w_{2b})$ to BS 1. It also sends $(w_{1a}, w_{2a}, w_{1c}, w_{2c})$ and the row index of $(\bar{u}_2^n, \bar{v}_2^n)$ in $C_{U_2, V_2 | U_0, V_0}(w_{1a}, w_{2a}, w_{1c}, w_{2c})$ to BS 2. It requires that

$$\hat{C}_k = Q_{10} + Q_{20} + R_{1k} - r_{1k} + R_{2k} - r_{2k} + r_{UVk} \leq C_k \quad k = 1, 2 \quad (25)$$

so that each BS can receive its index with no error.

At the BS, upon receiving $(w_{1a}, w_{2a}, w_{1b}, w_{2b})$ and the row index of $(\bar{u}_1^n, \bar{v}_1^n)$ in $C_{U_1, V_1 | U_0, V_0}(w_{1a}, w_{2a}, w_{1b}, w_{2b})$, BS 1 identifies the $(\bar{u}_1^n, \bar{v}_1^n)$ in $C_{U_1, V_1 | U_0, V_0}(w_{1a}, w_{2a}, w_{1b}, w_{2b})$ and sends the corresponding x_1^n as its transmitted signal. Similarly, upon receiving $(w_{1a}, w_{2a}, w_{1c}, w_{2c})$ and the row index of $(\bar{u}_2^n, \bar{v}_2^n)$ in $C_{U_2, V_2 | U_0, V_0}(w_{1a}, w_{2a}, w_{1c}, w_{2c})$, BS 2 identifies $(\bar{u}_2^n, \bar{v}_2^n)$ in $C_{U_2, V_2 | U_0, V_0}(w_{1a}, w_{2a}, w_{1c}, w_{2c})$ and sends the corresponding x_2^n as its transmitted signal.

The third part of proof is decoding. Upon receiving y_1^n , if there is a unique codeword triple $(u_0^n(\tilde{i}_0, \tilde{l}_0), u_1^n(\tilde{i}_0, \tilde{l}_0, \tilde{l}_1), u_2^n(\tilde{i}_0, \tilde{l}_0, \tilde{l}_2))$ where $(u_1^n(\tilde{i}_0, \tilde{l}_0, \tilde{l}_1), u_2^n(\tilde{i}_0, \tilde{l}_0, \tilde{l}_2))$ is in $C_{U_1, U_2 | U_0}(\tilde{i}_0, \tilde{l}_0, \tilde{i}_1, \tilde{i}_2)$ for some $(\tilde{i}_1, \tilde{i}_2)$, such that $(u_0^n(\tilde{i}_0, \tilde{l}_0), u_1^n(\tilde{i}_0, \tilde{l}_0, \tilde{l}_1), u_2^n(\tilde{i}_0, \tilde{l}_0, \tilde{l}_2), y_1^n)$ is jointly typical according to $p(u_0, u_1, u_2, y_1)$, then, the receiver of MU 1 declares that $(W_{1a}, W_{1b}, W_{1c}) = (\tilde{i}_0, \tilde{i}_1, \tilde{i}_2)$ is sent; otherwise, it declares an error.

Receiver 2 performs a similar decoding scheme as Receiver 1 when receiving y_2^n , which will not be described in details for simplicity.

The probability of error analysis, which is the final part of the proof, will present relative error events and the analysis for them. Due to symmetry, the average probability of error is equivalent to the probability of error for an arbitrary message pair (w_1, w_2) , where $(w_1, w_2) \in \{1, 2, \dots, 2^{nR_1}\} \times \{1, 2, \dots, 2^{nR_2}\}$. Hence, without loss of gener-

ality, it is assumed that $(W_1, W_2) = (\bar{w}_1, \bar{w}_2)$ is sent. For $W_1 = \bar{w}_1$ and $W_2 = \bar{w}_2$, denote $(W_{1a}, W_{1b}, W_{1c}) = (\bar{i}_0, \bar{i}_1, \bar{i}_2)$ and $(W_{2a}, W_{2b}, W_{2c}) = (\bar{j}_0, \bar{j}_1, \bar{j}_2)$, respectively.

First, consider the error event E_0 , where no jointly typical quadruple $(u_1^n, u_2^n, v_1^n, v_2^n)$ conditioned on $(u_0^n(\bar{i}_0, \bar{l}_0(\bar{i}_0, \bar{j}_0)), v_0^n(\bar{j}_0, \hat{m}_0(\bar{i}_0, \bar{j}_0)))$ can be found in $C_{U_1, U_2 | U_0, V_0}$ $(\bar{i}_0, \bar{j}_0, \bar{i}_1, \bar{i}_2)$ and $C_{V_1, V_2 | U_0, V_0}(\bar{i}_0, \bar{j}_0, \bar{j}_1, \bar{j}_2)$. By the mutual covering lemma^[16], $\Pr[E_0]$ approaches zero as $n \rightarrow \infty$ if

$$r_1 + r_2 \geq I(U_1, U_2; V_1, V_2 | U_0, V_0) \quad (26)$$

Given that E_0 does not occur, denote the jointly typical quadruplet found by CP as $(\bar{u}_1^n, \bar{u}_2^n, \bar{v}_1^n, \bar{v}_2^n)$, which is short for $(u_1^n(\bar{i}_0, \bar{l}_0, \bar{l}_1), u_2^n(\bar{i}_0, \bar{l}_0, \bar{l}_2), v_1^n(\bar{j}_0, \bar{m}_0, \bar{m}_1), v_2^n(\bar{j}_0, \bar{m}_0, \bar{m}_2))$, then consider the following error events for MU1:

E_{10} : $(u_0^n(\bar{i}_0, \bar{l}_0), \bar{u}_1^n, \bar{u}_2^n, y_1^n)$ is not jointly typical.

E_{11} : There exists a $u_1^n \in C_{U_1 | U_0}(\bar{i}_0, \bar{l}_0, i_1)$, denoted as $u_1^n(\bar{i}_0, \bar{l}_0, l_1)$. For some $i_1 \in [1: 2^{n(R_{11} - r_{11})}]$ such that $(u_0^n(\bar{i}_0, \bar{l}_0), u_1^n(\bar{i}_0, \bar{l}_0, l_1), \bar{u}_2^n, y_1^n)$ is jointly typical, and $u_1^n(\bar{i}_0, \bar{l}_0, l_1) \neq \bar{u}_1^n$, i. e., $l_1 \neq \bar{l}_1$.

E_{12} : There exists a $u_2^n \in C_{U_2 | U_0}(\bar{i}_0, \bar{l}_0, i_2)$, denoted as $u_2^n(\bar{i}_0, \bar{l}_0, l_2)$. For some $i_2 \in [1: 2^{n(R_{12} - r_{12})}]$ such that $(u_0^n(\bar{i}_0, \bar{l}_0), \bar{u}_1^n, u_2^n(\bar{i}_0, \bar{l}_0, l_2), y_1^n)$ is jointly typical, and $u_2^n(\bar{i}_0, \bar{l}_0, l_2) \neq \bar{u}_2^n$, i. e., $l_2 \neq \bar{l}_2$.

E_{13} : There exists a $(u_1^n, u_2^n) \in C_{U_1, U_2 | U_0}(\bar{i}_0, \bar{l}_0, i_1, i_2)$, denoted as $(u_1^n(\bar{i}_0, \bar{l}_0, l_1), u_2^n(\bar{i}_0, \bar{l}_0, l_2))$. For some $i_k \in [1: 2^{n(R_{1k} - r_{1k})}]$, $k = 1, 2$, such that $(u_0^n(\bar{i}_0, \bar{l}_0), u_1^n(\bar{i}_0, \bar{l}_0, l_1), u_2^n(\bar{i}_0, \bar{l}_0, l_2), y_1^n)$ is jointly typical, and $u_1^n(\bar{i}_0, \bar{l}_0, l_1) \neq \bar{u}_1^n, u_2^n(\bar{i}_0, \bar{l}_0, l_2) \neq \bar{u}_2^n$, i. e., $l_1 \neq \bar{l}_1, l_2 \neq \bar{l}_2$.

E_{14} : There exists a $(u_0^n(i_0, l_0), u_1^n(i_0, l_0, l_1), u_2^n(i_0, l_0, l_2))$, where $(u_0^n, u_2^n) \in C_{U_1, U_2 | U_0}(i_0, l_0, i_1, i_2)$. For some $i_k \in [1: 2^{n(R_{1k} - r_{1k})}]$, $k = 1, 2$, such that $(u_0^n(i_0, l_0), u_1^n(i_0, l_0, l_1), u_2^n(i_0, l_0, l_2), y_1^n)$ is jointly typical, and $(i_0, l_0) \neq (\bar{i}_0, \bar{l}_0)$.

At MU2, symmetric events $E_{20}, E_{21}, E_{22}, E_{23}$ may occur and the description for them, which will not be presented here, is similar to the above description for $E_{10}, E_{11}, E_{12}, E_{13}$.

Thus, the probability of error $\Pr[E]$ may be upper bounded as

$$\Pr[E_0] + \sum_{a=1}^2 \sum_{b=0}^4 \Pr[E_{ab} | E_0^c]$$

Due to the asymptotic equipartition property, for a sufficiently large n , it leads to $\Pr[E_{10} | E_0^c] \leq \varepsilon$ and $\Pr[E_{20} | E_0^c] \leq \varepsilon$. There is also

$$\Pr[E_{11} | E_0^c] = \sum_{i_1 \neq \bar{l}_1} \Pr[(u_0^n(\bar{i}_0, \bar{l}_0), u_1^n(\bar{i}_0, \bar{l}_0, l_1), \bar{u}_2^n, y_1^n) \in T_{\varepsilon}^n | E_0^c] \leq 2^{-n(I(U_1; Y_1, U_2 | U_0) - \varepsilon)} 2^{nR_{11}}$$

$$\Pr[E_{12} | E_0^c] = \sum_{i_2 \neq \bar{l}_2} \Pr[(u_0^n(\bar{i}_0, \bar{l}_0), u_1^n, u_2^n(\bar{i}_0, \bar{l}_0, l_2), y_1^n) \in T_{\varepsilon}^n | E_0^c] \leq 2^{-n(I(U_2; Y_2, U_1 | U_0) - \varepsilon)} 2^{nR_{12}}$$

$$\Pr[E_{13} | E_0^c] = \sum_{\substack{i_1 \neq \bar{l}_1 \\ i_2 \neq \bar{l}_2}} \Pr[(u_0^n(\bar{i}_0, \bar{l}_0), u_1^n(\bar{i}_0, \bar{l}_0, l_1), u_2^n(\bar{i}_0, \bar{l}_0, l_2), y_1^n) \in T_{\varepsilon}^n | E_0^c] \leq 2^{-n(I(U_1, U_2; Y_1, Y_2 | U_0) - \varepsilon)} 2^{n(R_{11} + R_{12} - I(U_1; U_2 | U_0) - \varepsilon)}$$

$$\Pr[E_{14} | E_0^c] = \sum_{\substack{i_0 \neq \bar{i}_0, i_1 \neq \bar{l}_1 \\ k=0, 1, 2}} \Pr[(u_0^n(i_0, l_0), u_1^n(i_0, l_0, l_1), u_2^n(i_0, l_0, l_2), y_1^n) \in T_{\varepsilon}^n | E_0^c] \leq 2^{-n(I(U_0, U_1, U_2; Y_1) - \varepsilon)} 2^{n(R_{10} + R_{11} + R_{12} - I(U_1; U_2 | U_0) - \varepsilon)}$$

Similar derivations follow $\Pr[E_{2k} | E_0^c], k = 1, 2, 3, 4$.

Thus, $\Pr[E]$ tends to zero as $n \rightarrow \infty$ if conditions (20) to (26) and the following set of constraints are satisfied:

$$\begin{aligned} R_{11} &\leq I(U_1; Y_1, U_2 | U_0) \\ R_{12} &\leq I(U_2; Y_2, U_1 | U_0) \\ R_{11} + R_{12} &\leq I(U_1, U_2; Y_1 | U_0) + I(U_1; U_2 | U_0) \\ R_{10} + R_{11} + R_{12} &\leq I(U_0, U_1, U_2; Y_1) + I(U_1; U_2 | U_0) \\ R_{21} &\leq I(V_1; Y_2, V_2 | V_0) \\ R_{22} &\leq I(V_2; Y_2, V_1 | V_0) \\ R_{21} + R_{22} &\leq I(V_1, V_2; Y_2 | V_0) + I(V_1; V_2 | V_0) \\ R_{20} + R_{21} + R_{22} &\leq I(V_0, V_1, V_2; Y_2) + I(V_1; V_2 | V_0) \\ 0 &\leq r_{mk} \leq R_{mk} \quad m = 1, 2, k = 0, 1, 2 \\ r_k, r_{UV_i}, \hat{C}_k &\geq 0 \quad k = 1, 2 \\ 0 &\leq Q_{k0} \leq R_{k0} \quad k = 1, 2 \\ R_m &= Q_{m0} + R_{m1} - r_{m1} + R_{m2} - r_{m2} \quad m = 1, 2 \end{aligned}$$

Using the Fourier-Motzkin elimination, the achievable rates (3) to (19) in Theorem 1 are obtained.

Aiming at a better understanding of Theorem 1, a few remarks are presented:

1) When $R_1 = Q_{10} = 0$, by setting $V_0 = V, V_1 = X_1, V_2 = X_2, Y_2 = Y, Q_{20} = R_0, U_0 = U_1 = U_2 = \emptyset$, the lower bound case in Ref. [3] is obtained.

2) By taking $U_0 = V_0 = \emptyset, Q_{10} = Q_{20} = 0$, the achievability scheme for the 2-destination multiple access diamond channel in Ref. [4] is obtained.

3) When C_1 and C_2 tend to infinity, by taking $U_1 = U_2 = V_1 = V_2 = \emptyset, U_0 = U, V_0 = V, Q_{10} = R_1$ and $Q_{20} = R_2$, which means that the full cooperation between BSs is achieved with the help of the superposition structure, Marton's inner bound for the general broadcast channel^[15] is obtained.

3 Numerical Results

The achievable region provided by Theorem 1 is for discrete memoryless channels. In this section, by considering the Gaussian nature of the channel, the achievable rate region is computed. First, specify the distributions $p(u_0, u_1, u_2, v_0, v_1, v_2), p(x_1 | u_0, u_1, v_0, v_1)$, and $p(x_2 | u_0, u_2, v_0, v_2)$. Combining the power allocation strategy^[17-18] for superposition coding in Ref. [14] and the dirty-paper strategy in Ref. [11], the following distribution is then proposed for the evaluation of the mutual information terms in Theorem 1.

First, consider zero-mean unit-variance jointly Gaussi-

an random variables U_0, V_0 with the correlation coefficient $\rho \in [-1, 1]$. Then, let

$$X_1 = U_1 + V_1 = \sqrt{A_1}U_0 + U'_1 + \sqrt{B_1}V_0 + V'_1 \quad (27)$$

$$X_2 = U_2 + V_2 = \sqrt{A_2}U_0 + U'_2 + \sqrt{B_2}V_0 + V'_2, \quad (28)$$

where X_k is the codeword with power P_k at BS k , $k = 1, 2$, (U'_1, U'_2, V'_1, V'_2) are Gaussian random variables independent of (U_0, V_0). A_1, B_1, A_2 and B_2 satisfy

$$\left. \begin{aligned} A_k, B_k &\in [0, P_{0k}] \\ A_k + 2\rho \sqrt{A_k B_k} + B_k &= P_{0k} \end{aligned} \right\} \quad (29)$$

where P_{0k} is the power allocated to (U_0, V_0) at BS k , $k = 1, 2$. Next, let \bar{X}'_k be a 2×1 Gaussian random vector with covariance matrix $\mathbf{K}_{\bar{X}'_k}$, $k = 1, 2$, where

$$\mathbf{K}_{\bar{X}'_1} = \begin{bmatrix} A & \alpha \\ \alpha & B \end{bmatrix}, \quad \mathbf{K}_{\bar{X}'_2} = \begin{bmatrix} P_1 - P_{01} - A & \beta \\ \beta & P_2 - P_{02} - B \end{bmatrix}$$

with

$$A \in [0, P_1 - P_{01}] \quad (30)$$

$$B \in [0, P_2 - P_{02}] \quad (31)$$

$$\alpha \in [-\sqrt{AB}, \sqrt{AB}] \quad (32)$$

$$\beta \in \left[-\sqrt{(P_1 - P_{01} - A)(P_2 - P_{02} - B)}, \sqrt{(P_1 - P_{01} - A)(P_2 - P_{02} - B)} \right] \quad (33)$$

Now, the dirty-paper coding is considered, where \bar{X}'_1 is considered as the channel state, i. e., let $\bar{U}' = \bar{X}'_1$ and $\bar{V}' = \bar{X}'_2 + A\bar{U}'$, where

$$A = \frac{1}{[b \ 1]\mathbf{K}_{\bar{X}'_1}\begin{bmatrix} b \\ 1 \end{bmatrix} + 1} \mathbf{K}_{\bar{X}'_1}\begin{bmatrix} b \\ 1 \end{bmatrix} \begin{bmatrix} b & 1 \end{bmatrix}$$

and \bar{X}'_2 and \bar{U}' are independent. Furthermore, let

$$\begin{bmatrix} \bar{X}'_1 \\ \bar{X}'_2 \end{bmatrix} = \bar{X}'_1 + \bar{X}'_2 = (\mathbf{I} - \mathbf{A})\bar{U}' + \bar{V}'$$

and

$$\mathbf{U}' = \begin{bmatrix} U'_1 \\ U'_2 \end{bmatrix} = (\mathbf{I} - \mathbf{A})\bar{U}', \quad \mathbf{V}' = \begin{bmatrix} V'_1 \\ V'_2 \end{bmatrix} = \bar{V}'$$

Based on the 4×4 covariance matrix of U'_1, U'_2, V'_1, V'_2 and conditions (1), (2), (27) and (28), by computing the sum rates in Theorem 1 under constraints (29) to (33), the optimal sum rate can be obtained.

In the case of $a = b = 0.9$, $P_1 = P_2 = 1$ and $C_1 = C_2 = C$, the achievable sum rate of the proposed superposition scheme is compared to the achievability scheme without the superposition structure in Ref. [4] and some other existing schemes in Fig. 2.

The upper bound of $\min\{2C, C_{\text{MIMO}}\}$ is denoted by the black dotted line, where C_{MIMO} is the capacity of the network when the backhaul capacity C is infinite. The red solid line denotes the sum rate of our superposition scheme and the green dashed line denotes the sum rate via the achievability scheme without the superposition struc-

ture^[11]. The magenta dash-dot line denotes the sum rate of the RCoF scheme in Ref. [10] and the blue solid line with circle markers denotes the sum rate of the compressed DPC scheme considering the correlation between the quantization noises^[7]. From Fig. 2, it can be seen that in the medium backhaul capacity region, our proposed scheme outperforms the RCoF scheme and compressed DPC scheme. Furthermore, when backhaul capacity C is relatively large, our superposition scheme outperforms the scheme without the superposition structure.

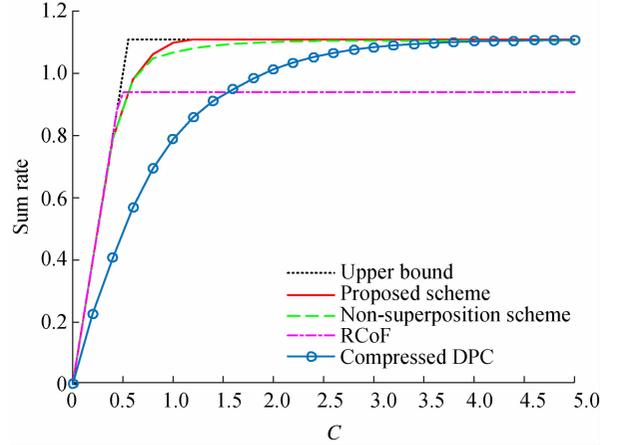


Fig. 2 The achievability sum rate vs. capacity of the backhaul link for $P = 1$, $a = b = 0.9$ and $C_1 = C_2 = C$

4 Conclusion

In this paper, the 2-BS-2-MU scenario of downlink multicell processing is studied. By viewing the problem as a multiple access diamond channel with two destinations, an achievability scheme exploiting the gain of correlation between the transmitted codewords is proposed, where superposition coding is introduced and it contributes to the superiority of the proposed scheme. The numerical simulation shows that the proposed scheme outperforms the existing achievability scheme without superposition coding when the capacities of backhaul link are relatively large. The inner codeword in this paper supports common data known at both BSs, and thus, enables more cooperation between the two BSs. As part of future work, a more involved superposition structure will be considered, where the inner codeword consists of not only the data decodable at both receivers as in the broadcast channel but also the common data sent to both BSs.

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有限容量回程链路的下行链路多小区处理的叠加编码策略

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摘要:在有限回程链路容量的下行链路多小区处理的场景中,针对2个基站2个用户的情况,通过将信道视为带有2个接收端的多址接入菱形信道,提出了一种可达性策略,将带有公共数据的相关码字传送到信道中.由于考虑了叠加编码的结构,该策略能够支持完全相关的码字,这使得在回程链路容量相对较大的情况下,系统吞吐量能够得到提升.首先给出了该可达性策略的可达域并从信息论的角度进行了证明.然后在高斯场景下,结合脏纸编码方法和功率分配方法,对可达域进行了仿真计算.仿真结果显示,当回程链路容量相对较大时,所提出的策略性能在某些情况下优于已知的未引入叠加编码的可达性策略.

关键词:多小区处理;有限回程链路容量;叠加编码;脏纸编码;功率分配

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