CoMP Joint Transmission for Gaussian Broadcast Channels in Delay-Limited Networks

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Abstract—The backhaul-linked cellular network architecture shows an intrinsic defect in its delay characteristic when Coordinated Multi-Point (CoMP) Joint Transmission (JT) is operated. Channel State Information (CSI) fed back to evolved Node B (eNB) is used to calculate joint BeamForming (BF) matrices and the results are delivered to helping eNBs, which participate in CoMP JT, through the backhaul link. The applied information, however, could be outdated before it reaches the helping eNBs due to the backhaul delay, thus resulting in the JT performance degradation as the UE velocity increases. Based on this observation, we propose a novel solution for Gaussian broadcast channels, which efficiently exploits the latest channel information available in the CoMP JT architecture. The numerical results clearly demonstrate the spectral efficiency gain of the proposed scheme at the cell-edge region, especially with high velocity and large backhaul delay.

Index Terms—Coordinated Multi-Point (CoMP) transmission/reception, Joint Transmission (JT), LTE-Advanced systems, backhaul delay.

I. INTRODUCTION

Coordinated Multi-Point (CoMP) transmission and reception, defined in Release 11 of the 3GPP LTE-Advanced specifications [1], arises as a promising technology for improving the cell-edge performance by the virtue of the evolved Node Bs (eNBs) cooperation via backhaul networks. Joint Transmission (JT) is one of the CoMP transmission scenarios, with which signals designated for a single User Equipment (UE) are simultaneously transmitted from multiple eNBs or Remote Radio Heads (RRHs) [1]. Assuming ideal backhaul networks, the multiple eNBs cooperating for JT can be regarded as one eNB with multiple distributed transmit antennas and individual group power constraints.

In real networks, however, the intrinsic defect of the backhaul delay can corrupt the BeamForming (BF) matrix: The channel information used for calculating BF matrix is naturally outdated before the actual data transmission. As an example, even with X2 interface, known as the fastest backhaul network defined in the 3GPP LTE-Advanced specifications [2], the delay for delivering Channel State Information (CSI) amounts to 20 ms [3]. Furthermore, the latency of copper, generic IP network, or wireless interface backhaul links can reach even up to tens of milliseconds [4]. The Release 12 of the 3GPP LTE-Advanced specifications [5] also tackles this point and suggests various scenarios considering backhaul delay up to 50 ms. The inaccuracy of the BF matrix becomes severer if the UE moves faster. Therefore, an efficient and robust beamforming is required in the real deployment of CoMP transmission.

The authors of [6] investigate an overview of the information-theoretic results as well as existing coding and beamforming techniques for multi-cell cooperation in wireless cellular networks. They specifically deal with the scenario with the practical backhaul constraint and try to enhance capacity, but do not cover backhaul latency. The work [4] proposes a sequential and incremental eNB-wise precoder design for downlink JT considering the practical backhaul delay. This work, however, focuses on the flexible attach and detach of the helping eNBs according to the network quality, and does not pay attention to the channel corruption caused by the backhaul delay. In addition, it just tries to minimize Mean Square Error (MSE) in the worst case scenario, but does not provide a solution maximizing fundamental measure such as spectral efficiency.

Motivated by this, we propose a novel solution improving the spectral efficiency of CoMP JT. Considering the accuracy of the CSI is different between the primary eNB and the helping eNBs, eNB-wise sequential beamforming strategy is proposed in two steps by solving an optimization problem. The performance evaluation results demonstrate the significant gain of the proposed scheme over the conventional JT scheme.

The following notations are employed in this paper. Boldface capital letters and boldface small letters are used to denote matrices and vectors, respectively. Superscript $H$ denotes conjugate transpose. $\text{det}()$ represents the determinant of a matrix, $tr()$ denotes the trace of a matrix, and $I_N$ stands for an identity matrix with cardinality of $N$. An $M \times N$ matrix with all zero elements is denoted by $0_{M \times N}$.

II. CoMP JT ARCHITECTURE

In this paper, LTE-Advanced downlink systems operated by CoMP JT mode is considered. $L$ cooperating eNBs equipped with $N_t$ transmit antennas and $K$ UEs equipped with $N_r$
The achievable rate of UE $k$ is given by
\[
R_k = \log_2 \det \left( \sum_{j=1}^{K} \bar{H}_k Q_j \bar{H}_k^H + \sigma^2 I \right) - \log_2 \det \left( \sum_{j \neq k} \bar{H}_k Q_j \bar{H}_k^H + \sigma^2 I \right)
\]
where $Q_j = \hat{F}_j \hat{F}_j^H$. Then, the sum rate maximization problem of the conventional JT is formulated as
\[
\text{maximize } Q_j \geq 0, v_j \quad \text{subject to } \quad \sum_{k=1}^{K} R_k \leq P_l \quad \forall l.
\]

The constraint represents the per-eNB power limits, i.e., power limit $P_l$ of a cooperating eNB $l$, for which we define $E_l$ as
\[
E_l = \begin{bmatrix} 0_{N_t} & \cdots & I_{N_t} & \cdots & 0_{N_t} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ 0_{N_t} & \cdots & I_{N_t} & \cdots & 0_{N_t} \end{bmatrix}.
\]

After solving the problem (3), the BF matrix of eNB $l$ for UE $j$ can be updated as the $N_r$ leading eigenvectors of the matrix $E_l Q_j F_j^H$, multiplied by the square roots of the corresponding eigenvalues. However, since the objective function of (3) is not concave, we cannot directly solve the problem. We need an approach to find an alternative solution for the given problem, which will be explained in Section III.

The message exchange flow among the cooperating eNBs and UE for conventional JT is illustrated in Fig. 1. After receiving Channel State Information Reference Signals (CSI-RSs) periodically broadcasted by eNBs, UE estimates the downlink channel from all the cooperating eNBs and feeds back the CSI to the primary eNB. The primary eNB calculates the BF matrices according to (3) based on the channel feedback information of both primary and helping eNBs. The resulting BF matrices of the helping eNBs are sent to the corresponding eNBs, respectively. Considering the CoMP architecture, one of the eNBs should have an authority to calculate the BF matrices of cooperating eNBs in a designated frequency band. In this paper, we assume that the primary eNB is the one properly selected to have the authority and the JT beamforming is performed to the UEs associated to the same eNB in the corresponding frequency band.

Note that the CSI is fed back only to the primary eNB from UE so that the BF matrices of helping eNBs are calculated by the primary eNB and transferred to the helping eNBs through backhaul link. Therefore, the information of BF matrices calculated at the primary eNB can be outdated severely before delivered to the helping eNBs in practical delay-limited networks. The degree of inaccuracy of BF matrix increases as the backhaul delay and UE mobility increases in a fast fading channel.

Fig. 1. The data transmission procedure of the conventional JT.
III. PROPOSED SCHEME

If the backhaul delay time can be estimated so that a synchronized JT from all the cooperating eNBs is available, the BF matrix of the primary eNB can be refined again before the data transmission reflecting its latest channel information. However, only the BF matrix of the primary eNB can be refined right before the data transmission because the BF matrices of helping eNBs cannot reflect the latest channel information due to the backhaul delay. This additional refinement procedure is highlighted by the dotted box in Fig. 2.

The first step of the procedure is the same as that of the conventional JT as described in Section II. After sending the BF matrices to the corresponding eNBs based on the initial channel feedback, the proposed eNB-wise Adaptive BeamForming (eA-BF) re-calculates the BF matrix of the primary eNB after backhaul delay time has passed. The latest CSI-RS feedback is used so that the most accurate channel information could be reflected. At this step, the BF matrices of the helping eNBs are set as constants and only the BF matrix of the primary eNB is updated. Specifically, it is expressed as

\[
\begin{align*}
\max_{Q_{j} \succeq 0, j} & \sum_{k=1}^{K} R_{k} \\
\text{s.t.} & \quad tr \left( B_{i} \left( \sum_{j=1}^{K} Q_{j} \right) B_{i}^{H} \right) \leq P_{i}, \\
& \quad B_{r \leftarrow j} Q_{j} B_{i}^{H} = F_{r \leftarrow j} F_{i \leftarrow j}^{H}, \quad \forall j,
\end{align*}
\]  

(4)

where \( B_{i} = [I_{N_{i}}, 0_{N_{i} \times (N_{i}-(L-1))}] \) and \( B_{r \leftarrow j} = [0_{(N_{r}-(L-1)) \times N_{i}}, I_{N_{r}-(L-1)}] \).

Compared to the original problem (3), we now have an additional constraint that imposes the BF matrices for the helping eNBs to be fixed. \( F_{r \leftarrow j} \) indicates the concatenation of these matrices for UE \( j \) and has already been derived by (3) at the previous step. Moreover, the matrix \( H_{k} \) used to determine \( R_{k} \) in (4) is the updated channel matrix rather than the outdated one used in (3).

However, the objective functions of (3) and (4) are not concave since they are the difference of two concave functions. Among the known algorithms for solving this kind of problems [7], [8], we here employ the Majorization Minimization (MM) algorithm [9] as described in Algorithm 1, where \( Q^{(t)} \) represents \( \{Q_{j}^{(t)}\}_{j=1}^{K} \). It is an iterative algorithm solving a concave problem at each iteration by linearizing one of the concave parts in the objective function. In order to solve the problem (3), only the constraints in Algorithm 1 are needed to be changed accordingly.

The linearizing function \( \varphi_{k} \left(Q^{(t+1)}, Q^{(t)}\right) \) in Algorithm 1

**Algorithm 1** MM Algorithm for the problem (4)

1: Initialize \( Q^{(t)} \) to be arbitrary positive semidefinite matrices satisfying the constraints in (4) and set \( t = 1 \).

2: Update \( Q^{(t+1)} \) as the solution of the following concave problem:

\[
\begin{align*}
\max_{Q_{j}^{(t+1)} \succeq 0, j} & \sum_{k=1}^{K} \log_{2} \det \left( \sum_{j=1}^{K} H_{k} Q_{j}^{(t+1)} H_{k}^{H} + \sigma^{2} I \right) \\
\text{s.t.} & \quad tr \left( B_{i} \left( \sum_{j=1}^{K} Q_{j}^{(t+1)} \right) B_{i}^{H} \right) \leq P_{i}, \\
& \quad B_{r \leftarrow j} Q_{j}^{(t+1)} B_{i}^{H} = F_{r \leftarrow j} F_{i \leftarrow j}^{H}, \quad \forall j,
\end{align*}
\]

3: Stop if \( \sum_{k=1}^{K} \left(R_{k}^{(t+1)} - R_{k}^{(t)}\right) < \delta \) with predefined threshold value \( \delta \). Otherwise, set \( t \leftarrow t + 1 \) and go back to Step 2.
is defined as
\[
\varphi_k \left( Q^{(t+1)}, Q^{(t)} \right) = \psi \left( \sum_{j \neq k} \bar{H}_k Q_j^{(t+1)} \bar{H}_j^H + \sigma^2 I, \sum_{j \neq k} \bar{H}_k Q_j^{(t)} \bar{H}_j^H + \sigma^2 I \right),
\]

where
\[
\psi(X, Y) = \log_2 \det(Y) + \frac{1}{ln2} tr(Y^{-1}(X - Y)).
\]

Note that the function (5) is the first-order Taylor series expansion of the second term in (2) at \( Q^{(t)} \). Then, it becomes a global over-estimator of the corresponding term so that we can apply the MM algorithm. Furthermore, it is proven that the sum rate monotonically increases with respect to the iteration index \( t \). [10]

The key concept of eA-BF is to refine only the BF matrix of the primary eNB against with the latest channel information just before data transmission. This guarantees the most accurate information in calculating BF matrix of the primary eNB regardless of the backhaul delay, whereas the BF matrices of the helping eNBs are fixed as the initial values. This concept does not cause much overhead because the proposed scheme just uses CSI which is being fed back periodically in the system. Thus, in the delay-limited networks, eA-BF can provide significant gain compared to the conventional JT with low signaling overhead.

IV. PERFORMANCE EVALUATION

In this section, the performance of the proposed scheme is evaluated and compared with the conventional JT using a MATLAB-based system-level simulator, incorporating practical channel and system environments of 3GPP LTE-Advanced systems. We assume that there are three eNBs connected through wired backhaul link and three UEs located in the middle of them as depicted in Fig. 3 by setting all the pathloss values to be equal. This model is useful for verifying the performance of the worst case UEs at the cell-edge region. We assume that each UE is associated to one eNB. The numbers of antennas of eNBs and UEs are set to four and one, respectively. Orthogonal Frequency Division Multiplexing (OFDM) transceiver is assumed and the Modified Ped. B model of ITU-R as an OFDM channel delay profile is employed as channel delay profile [11]. A ray-based model considered in IEEE 802.16m Evaluation Methodology Document (EMD) is also applied for a Multiple-Input Multiple-Output (MIMO) Spatial Channel Model (SCM) [12]. The channel matrix \( \mathbf{W}_i \) is updated every 1 ms according to a Markov chain, \( \mathbf{W}_i(n + 1) = \rho \mathbf{W}_i(n) + \sqrt{1 - \rho^2} \mathbf{N}_n \), where the elements of \( \mathbf{N}_n \) are i.i.d. Gaussian random variables with zero mean and variance 1/2. The correlation coefficient is defined by \( \rho = J_0^2(2 \pi f_D \Delta t) \), where \( J_0 \) is the zero-order Bessel function of the first kind and \( \Delta t \) is a slot time which is set to 1 ms. \( f_D \) refers to the Doppler frequency, which is described by \( f_D = v f_c / C \), where \( v \) is the velocity of the UE, \( f_c \) is the carrier frequency, and \( C \) is the speed of light. More specific simulation parameters are included in Table I.

As reference schemes, Ideal BF, Open-loop BF, and Singlecell BF are also compared with the conventional JT and proposed scheme. The Ideal BF always uses the exact channel information at every time slot for both primary and helping eNBs. Therefore, the penalty of the feedback and the backhaul delay is ignored and the performance upper-bound is demonstrated. In the case of Open-loop BF, three eNBs cooperate with each other, but they just use a fixed BF matrix which does not depend on the channel information. For Singlecell BF, there is no cooperation among eNBs and each eNB just conducts a beamforming to its own associated UE so that severe interference from other eNBs cannot be avoided.

Fig. 4 represents the average sum rate for each scheme as the UE velocity increases when the backhaul delay is 20 ms. The proposed eA-BF achieves 75% gain over the conventional JT when UE velocity is 10 m/s, whereas it shows small performance gain when UE velocity is 1 m/s. Unlike the conventional JT, eA-BF additionally updates the BF matrices for UEs’ associated eNB before transmission so that eA-BF outperforms the conventional JT. The performance gain of the proposed scheme compared to the conventional one increases as the UE velocity increases. The effect of updating the BF matrix becomes critical for the high speed UE since the fast
channel variation deteriorates the reliability of the channel feedback.

Fig. 5 shows the average sum rate according to the increment of the backhaul delay when the UE velocity is 10 m/s. The eA-BF shows improved performance compared to the conventional JT in the presence of the backhaul delay. It shows 58% gain compared to the conventional JT when the backhaul delay is 10 ms. When the backhaul delay is zero, the performance of the conventional JT and eA-BF is the same because there is no room for further improvement. However, even with zero backhaul delay, these two schemes perform worse than Ideal BF because of the non-zero feedback period during which the channel information cannot be updated. The other reference schemes, i.e., Ideal BF, Open-loop BF, and Singlecell BF clearly demonstrate static performance across varying backhaul delay.

V. CONCLUSION

We have proposed a CoMP JT beamforming scheme that is robust for delay-limited networks. The proposed eNB-wise Adaptive Beamforming (eA-BF) employs two step sequential beamforming so that the BF matrix of the primary eNB can be refined again based on the latest channel information. Through the system-level simulation, we have demonstrated that eA-BF outperforms the conventional JT, for example, by achieving 75% gain when the UE velocity is 10 m/s and the backhaul delay is 20 ms.

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