Energy Efficient Feedback Design for Coordinated Multi-Point Transmission in Downlink

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Abstract

Coordinated multi-point (CoMP) has been raised to increase the average cell throughput and the cell-edge user throughput. However, the energy consumption of mobile stations (MSs) is a key problem restricting the wide application of CoMP systems. Considering the energy consumption of feeding back channel state information (CSI) by MSs and the influence of CSI accuracy on the throughput of system, it is proposed to measure the relationship between feedback energy consumption and throughput with energy efficiency feedback utility (EEFU) function which can adapt to different application scenes by adjusting utilization coefficient. The feedback utilization of two precoders in CoMP systems is analyzed respectively, including the optimization allocation of feedback bits with utility function. The complete EEFU optimized expression and the optimizing flow path satisfying the actual application demands of CoMP systems are then derived. The simulation results illustrate the practicability and necessity of the EEFU function and verify the performance of EEFU with different precoders.

Keywords: CoMP, LTE, energy efficiency, precoder, CDI

1. Introduction

With the rapid development of 3GPP standardization on LTE-Advanced, coordinated multi-point (CoMP) transmission technology receives more and more attention, which can reduce the inter-cell interference and improve the spectrum efficiency at the cell edge through the cooperation among adjacent base stations (BSs) [1]. CoMP can be generally divided into two categories, i.e., CoMPjoint processing (CoMP-JP) and CoMPcoordinated beamforming or scheduling (CoMP-CB/CS). The former requires sharing the data and channel state information (CSI) among BSs to facilitate the joint precoding, while the latter can work when scheduling information and CSI of the serving cell are shared [2, 3]. Compared to CoMP-CB/CS, CoMP-JP can exploit the abundant spatial resources provided by the cooperating BSs, and provide higher spectrum efficiency [4]. Therefore, CoMP-JP is concerned in this paper. In the rest of the papers, CoMP-JP is CoMP for simplicity. And a multi-cell single-user CoMP system is focused to study the feedback energy efficiency, which is important for energy-limited mobile stations (MSs).

Precoding is always employed in the downlink CoMP to achieve good performance at MSs with low computation capability. MSs must feedback CSI to BSs if frequency division duplex (FDD) is considered. The system performance highly depends on the quality of CSI. Since the perfect CSI is impossible in practice, codebook based CSI is widely adopted, where only the space direction of the channel, namely channel direction information (CDI), is considered while
channel quality information (CQI) is obtained from long-term statistics or perfectly known at the cooperating BSs [5].

In point-to-point MIMO systems, a CDI codebook with fixed size could be used. The larger the codebook, the more precise the CSI and hence the better the performance of precoding [6]. In the CoMP considering multi-point transmission, the received signals at the MS from different BSs have different qualities since the channels between the MS and BSs are independent to each other. Hence, from each downlink between a BS and the MS, the corresponding space direction is different. Since the number of MSs change frequently, a large size global codebook, which is much more complex than the per-cell codebook, needs to be re-designed from time to time. This means that fix-sized global codebook is not suitable for the dynamic situations in CoMP and brings in enormous overhead [7]. Therefore, it is proposed that per-cell codebooks, which are also considered in this paper, should be designed for CoMP based on the limited feedback [8].

Note that CoMP is employed to improve the performance of cell-edge MSs, whose transmission power is much higher than those in cell-center due to the larger transmission distance. Moreover, in the practical LTE systems, the CSI feedback cycle is designed to be multiple of 5ms according to the radio frame structure, and it would be taken as a long-term feedback if the cycle is 20ms [9]. Therefore, when codebook based CoMP is employed in the downlink transmission for cell-edge MSs, the CSI feedback is quite frequent. Given the high transmission power of cell-edge MSs, the feedback energy consumption would be large. Since MSs are power-limited, it is necessary to design the energy-efficient feedback schemes for CoMP in downlink transmission.

In this paper, an energy efficiency feedback utility (EEFU) function is firstly defined as the system performance metric. Then, considering the macro-diversity CoMP where multiple BSs transmit signals to one cell-edge MSs, per-cell CSI feedback schemes are designed for different precoding algorithms, such as maximum ratio transmission (MRT), minimum mean square error (MMSE) and zero forcing (ZF). It is shown in simulation that the optimization of the EEFU function helps the CoMP networks under different precoders to make better use of the feedback energy of MS.

The rest of the paper is organized as follows. In Section 2, the system model is described. In Section 3, the allocation of feedback bits is optimized with the calculation of EEFU under several types of precoder. Simulation results are provided in Section 4, and the conclusion is given in the last section.

2. System Model

A downlink CoMP is considered in the heterogeneous networks consisting of macro BSs and pico BSs with different transmission powers. As shown in Fig. 1, the cooperation could be carried out among adjacent macro BSs and/or pico BSs. To focus on the precoding performance and feedback scheme of CoMP, it is assumed that the backhaul link has sufficient capacity. Thus, the cooperative BSs can share the transmission data and feedback information perfectly to realize joint processing and transmission.

Suppose there are N BSs in a CoMP cooperating set, and each BS, high or low power node, is equipped with N antennas [10]. These cooperating BSs are combined to transmit data to the MS with a single antenna. Denote the small-scale fading channel from the BS to the MS as $h_n \in \mathbb{C}^{1 \times N}$, and the corresponding large-scale fading as $\alpha_n$. Without loss of generality, assume that $E(\|h_n\|_2^2) = 1$, where $\| \cdot \|_2$ is the Euclidian norm. The small-scale fading channels from BSs in the CoMP cooperating
set to the MS is  
\[ h = [h_1, \cdots, h_N]^T \in \mathbb{C}^{N \times N}, \]
while the large-scale fading is 
\[ a = \text{diag} \left( \alpha_1, \cdots, \alpha_N \right) \in \mathbb{C}^{N \times N}, \]
where \( \text{diag}(.) \) is the diagonal matrix taking only the diagonal terms of a matrix.

Assuming that the feedback bits from the MS to BS \( n \) is \( B_n \), a random vector quantization (RVQ) codebook \( C_n \) of size \( 2^h \) is used, where 
\[ C_n = \{ c_1, c_2, \cdots, c_{2^h} \}. \]
The quantized CDI of the per-cell channel \( h_n \) is given by
\[ h_n = \arg \max_{c \in \mathbb{C}^h \colon \|c\|_2 \leq 2^h} \|h_n c\|_2 \quad (1) \]
where \( c \in C_n \).

Denote the precoding matrix of the MS as 
\[ W = (W_1, \cdots, W_N) \in \mathbb{C}^{N \times N}. \]
The transmission power matrix is 
\[ P = \arg \left( \sqrt{P_1, \cdots, \sqrt{P_N}} \right) \in \mathbb{C}^{N \times N}. \]
\( n_s \) is the independent information symbol with unit power from the MS to the BS, 
\( E\left( n_s^* n_s \right) = 1 \), and the signal transmitted is denoted as a vector \( s \in \mathbb{C}^{N \times 1}. \) The receiving signal of the MS is given as
\[ y = a h W s + n \quad (2) \]
where \( n \in \mathbb{C}^{N \times 1} \) is the noise.

Linear precoding is considered in this paper due to its low complexity, such as MRT, ZF and MMSE. The target of MRT precoding is to maximize the received SNR at MS under the power constraints, but it neglects the effect of interference. On the other hand, ZF precoder mainly eliminates the co-channel interference. As for MMSE precoder, it minimizes the mean square error between the source signal and received signal through the combined optimization design of precoding and decoding matrix. In CoMP systems, if a central unit controls the transmission of BSs, the noise will have greater impact on the system since the inter-cell interference is turned into desired signals [11].

In ZF precoding, the precoding vector \( W \) is the null space of other user’s channel matrix and orthogonal with other channel direction vector [12]. It has been shown that in realistic cellular scenarios, ZF precoding matrix can be simplified as CDI [13]. Therefore, in following contents, MRT and MMSE precoding are considered and ZF precoding is included in MRT.

**Figure 1. CoMP in a Heterogeneous Network**
3. Energy Efficient Feedback Design

In this section, the EEFU function for CoMP is proposed at first, then the EEFU for two linear precoding methods, MRT and MMSE, are analyzed, including the optimization scheme and corresponding flow path of utility maximization.

3.1. EEFU Function for CoMP

Since CDI is fed back from the MS to BS frequently, it is closely related to the MS power consumption. Besides the power needed for feedback, a major power consumption is caused by the signal processing at the MS [14]. Considering the two kinds of energy, energy efficiency (EE) of the MS is defined as

$$ f_{EE} = \frac{f_{SE}}{P_{tot}} = \frac{\log_2(1+\gamma)}{P_{op} + P_{fb}} $$

(3)

Where $f_{SE}$ is the spectrum efficiency (SE), $P_{tot}$ is the energy consumption and $\gamma$ is the downlink SNR at the MS. Since the single user CoMP is concerned, there is no interference. $P_{op}$ consists of static energy $P_{sp, st}$ and dynamic processing energy $P_{sp, dy}$[15].

$P_{fb} = P_b \sum_{n=1}^{N} B_n$, where $P_b$ is the energy of each feedback bit.

Considering the importance of EE and SE to MSs in CoMP systems, an adaptive coefficient should be employed to balance them. Hence, the unified EEFU function is defined as

$$ f(B_{sum}, \mu) = \frac{\log_2(1+\gamma)}{(P_{op} + P_{fb})^\mu} $$

(4)

Where $B_{sum}$ is the total number of feedback bits from the MS. According to the system requirement, the utility coefficient $\mu$ could be adjusted to optimize EE and SE:

1) when $\mu=0$, the system is only interested in SE, and the cost of feedback energy consumption can be ignored;
2) when $\mu=1$, the system is quite sensitive to the MS energy and feedback energy consumption;
3) when $0<\mu<1$, the system concerns both the SE and power consumption at the MS. Usually, the system should select a parameter $\mu$ between 0 and 1.

It can be seen that the unified EEFU can be optimized over the total power consumption by taking a derivation over $P_{tot}$.

$$ f'(B_{sum}, \mu) = \frac{f_{SE}}{P_{tot}^\mu} \left( f_{SE} \right)^{\mu-1} \left( \frac{f_{SE} P_{tot} - \mu f_{SE} P_{tot}'}{P_{tot} P_{tot}'} \right) $$

(5)

When $\mu=0$, the derivation of SE equals to $f'(B_{sum}, 0) > 0$, so the demand of SE will be met with increasing feedback bits. Considering $f_{SE} P_{tot} - f_{SE} P_{tot}' \leq f_{SE} P_{tot} - 0 \cdot f_{SE} P_{tot}'$, if $f'(B_{sum}, 1) > 0$, $f'(B_{sum}, \mu) > 0$ and the EE and SE will present increasing trends in accordance with the bits regardless of $\mu$. If $f'(B_{sum}, 1) < 0$, the EEFU will change from increasing to decreasing trend when $\mu$ increases from 0 to 1. When $\mu$ is relatively small, it reflects more about the condition of SE. On the contrary, more attention will be paid to energy conservation along with large $\mu$. Furthermore, In order to guarantee that the system outage probability is not too high, SE shall at least reach the minimum limit $R_{ou}$, i.e. $f(B_{k, sum}, 0) \geq R_{ou}$. 


3.2. EEFU for CoMP based on MRT Precoding

Assume that MRT precoding is employed at the cooperating BSs, where the precoding vector shall be CDI. Then, the received signal can be expressed as in (2) with the precoding matrix given by

$$W = (h_1^H, h_2^H, \ldots, h_N^H)$$

where $(\cdot)^H$ is the conjugate transpose of a vector or a matrix. Then, the received signal can be expressed as in (2) with the precoding matrix given by

$$\gamma = E[\frac{\sum_{n=1}^{N} \sqrt{P_n} \alpha_n h_n^H h_n^*}{\sigma^2}] = T_1 E \left[ \sum_{n=1}^{N} \beta_n h_n^H h_n^* \right]$$

where $\sigma^2$ is the noise power, $T_1 = 1/\sigma^2$ and $\beta_n = \sqrt{P_n \alpha_n}$.

Assume that the per-cell quantized method is employed. Note that form (1), the phase $\angle (h_i^H)$ distributes evenly in $[0, 2\pi]$ and is independent with each other for different $i$. Therefore, (7) can be rewritten as

$$\gamma = T_1 \sum_{n=1}^{N} E[\beta_n] E[\|h_n^H h_n^*\|_2]$$

According to [16], CDI quantization distortion is given by

$$E[\|h_n^H h_n^*\|_2] = 1 - N_f^{-1} 2^{-\frac{B_n}{N_f-1}}$$

Substituting (8) and (9) into (4) gives

$$f(B_{sum}, \mu) = \log_2 (1 + T_1 \! \sum_{n=1}^{N} E[\beta_n] \! (1 - \! \frac{N_f^{-1}}{2^{-\frac{B_n}{N_f-1}}}))$$

$$\frac{(P_p + P_h)^\mu}{(P_p + P_h)^\mu}$$

The concavity and convexity for the above equation of both two variables cannot be estimated easily, and both the numerator and denominator will increase with the number of feedback bits. However, it can be seen that when the total bits $B_{sum}$ is fixed, there will be at least one bit allocation method which will maximize the unified EEFU. Considering that the number of feedback bits would be limited in practice, the maximization of the unified EEFU can be carried out as follows.

1) Given $B_{sum}$, the allocation scheme for maximization the unified EEFU worked out as follows.

The object function of the allocation scheme is the numerator of (10) which can be simplified with Karush-Kuhn-Tucker (KKT) condition as follows:

$$\min \ g_1(B) = \sum_{n=1}^{N} E[\beta_n] 2^{-\frac{B_n}{N_f-1}}$$

s.t. $\sum_{n=1}^{N} B_n = B_{sum}, \ n = 1, 2, \ldots, N$
\[ B_n = \text{round} \left[ (N_n - 1) \left( \log_2 \left( \frac{\|\beta_n\|_2^2}{R_n} \right) - \log_2 \left( \lambda_n \right) \right) \right] \] (12)

where \( [x]^\dagger = \max(0, x) \), \( \lambda_n = \ln 2 \), \( \text{round} \) is the nearest integer function. \( \lambda \) can be further obtained

\[ \lambda = \frac{\|\beta_n\|_2^2}{R_n} = \left( \frac{\prod_{i=1}^{N} \|\beta_i\|_2^2}{R_{\max}} \right)^{\frac{1}{N}} \] (13)

2) Given the optimized bits allocation for each possible \( B_{\text{sum}} \), the one which can maximize (10) will be selected.

\[ f_{\text{sp}}(B_{\text{sum}}, \mu) = \max \left( \log_2 (1 + \sum_{n=1}^{N} E[\|\beta_n\|_2^2 (1 - \frac{N_n - 1}{N_n} \frac{R_n}{2^{N_n-1}})]) \right) \quad B_{\text{sum}} = 1, 2, \ldots, \sigma \] (14)

3.3 EEFU for CoMP based on MMSE Precoding

According to (2), the receiving signal of the MS can be obtained from the joint optimization of precoding matrix \( W \) and decoding matrix \( G \) under the MMSE criterion

\[ \hat{s} = Gy = G(ahWps + n) \in \mathbb{C}^{N \times 1} \] (15)

Where \( W \) and \( G \) are obtained as

\[ \{W, G\} = \arg \min_{\{W, G\}} E[\|\hat{s} - s\|_2^2] \] (16)

The small-scale fading channel \( h \) can also be written as

\[ h = ch + dq \] (17)

where \( h \in \mathbb{C}^{N \times 1} \) is the channel after quantization and \( q \in \mathbb{C}^{N \times 1} \) is the quantized error vector that is orthogonal with \( h \). Moreover, it can be obtained that

\[ c = [\cos \theta_1, \cos \theta_2, \ldots, \cos \theta_N] \in \mathbb{C}^{1 \times N} \]

\[ d = [\sin \theta_1, \sin \theta_2, \ldots, \sin \theta_N] \in \mathbb{C}^{1 \times N} \] (18)

where \( \cos \theta_n = \|h, h_n\| \) measures the accuracy of the quantization.

According to (16), the optimum precoding and decoding matrix could be obtained as follows:

\[ W = \left(h^H a^H G^H Gah \right)^{-1} h^H a^H G^H P^H \left(P P^H \right)^{-1} \] (19)

\[ G = PW^H h^H a^H R_n^{-1} = P^H h^H W^H h a^H \left(ahWPP^H W^H h a^H + R_n \right)^{-1} \] (20)

where

\[ R_n = E[yy^H] = ahWPP^H W^H h a^H + R_n \text{, } R_n = E[nn^H] \text{.} \]

Then, the received SNR of the MS turns out to be
\[ \gamma = E \left[ \frac{|ahWPr|_2^2}{|n|_2^2} \right] = E \left[ \frac{|ah(h^H a^H G a h)^{-1} h^H a^H G a P a h (P a)^{-1} P s|_2^2}{|n|_2^2} \right] \]  

(21)

Denoting \( \bar{a}_h = ah \in C^{N_t N_r} \) and \( \alpha_h = (ah)^H \in C^{N_t N_r} \), it can be learned that the above equation is related to the numerator, i.e.,

\[ E \left[ \frac{|ah(h^H a^H h^{-1} h^H a^H a_h) - a_h|_F^2}{|n|_2^2} \right] = E \left[ \frac{|\bar{a}_h (a_h a_h)^{-1} a_h|_F^2}{|n|_2^2} \right] \]  

(22)

Substituting \( \bar{a}_h = \begin{pmatrix} \alpha_h \ h_1 \\ \vdots \\ \alpha_h \ h_N \end{pmatrix} \) and \( a_h = \begin{pmatrix} \alpha_h \ h_1 \\ \vdots \\ \alpha_h \ h_N \end{pmatrix} \) into (22) gives us

\[ E \left[ \frac{|\bar{a}_h (a_h a_h)^{-1} a_h|_F^2}{|n|_2^2} \right] = E \left[ \frac{|\bar{e}_h|_F^2}{|n|_2^2} \right] = \sum_{n=1}^N \left[ 1 - \frac{N_r - 1}{N_t} \right]^{-\frac{B_s}{N}} \]  

(23)

Thus, the solutions to \( B_s \) can be obtained by maximizing (23) without considering transmit power or distance, leading to equal allocation of bits among BSs. Therefore, the feedback resource allocation problem based on MMSE precoding can be independent of transmission energy or distance. And the rest part of the algorithm is similar to the EEFU algorithm for MRT precoding.

4. Simulation Results

This part verifies the performance of the proposed energy efficient feedback design scheme based on the unified EEFU for CoMP networks.

In the simulations, the CoMP cooperating set consists of three BSs, which are about 0.05 km, 0.3 km and 0.5 km away from the concerned MS, respectively. When homogeneous networks are considered, the three BSs are all macro BSs with a transmit power of 46 dBm [17]. On the other hand, when a heterogeneous network is concerned, the closest BS becomes a pico BS with a transmit power of 30 dBm [17]. Large-scale fading model is \( PL(dB) = 128.1 + 37.6 \log_{10}(d(km)) \) [18]. Let \( \sigma^2 = 1 \) and \( N_r = 4 \). The values of \( P_{sp} \) and \( P_{fb} \) are related to the types of specific equipment. According to [4] and the energy consumption of mobile terminal, let \( P_{sp, c} = 0.5 W, P_{sp, dy} = 0.01 W, \) and \( P_{fb} = 10 \mu J/b \) [19]. The feedback cycles can be 5, 10 and 20 ms [9]. In the following evaluations, the normalized EEFU is employed for better illustration, which is the ratio of the EEFU value and the maximum value of the utility.

Given the utility coefficient \( \mu = 1 \), Fig. 2 illustrates the optimum total number of feedback bits \( B_{sum} \) for different feedback cycles. It can be seen that for any given feedback cycle, the normalized EEFU increases first as \( B_{sum} \) increased from a small value. Then a maximum EEFU is obtained at a certain \( B_{sum} \). As \( B_{sum} \) increased further, EEFU decreased. This is because SE gain resulting from feedback CDI precision cannot compensate the increase in feedback energy after the certain \( B_{sum} \).
**Figure 2.** Normalized EEFU versus Total Number of Feedback Bits under Different Feedback Cycles

**Figure 3.** Impact of $\mu$ on the Normalized EEFU

**Figure 4.** Allocation Ratio of Feedback Bits among Three Macro BSs
When the feedback delay cycle is larger, the corresponding optimum $B_{\text{sum}}$ is also larger. As the feedback cycle reduces, the feedback frequency increases, and the denominator of (4), $1/P_{\mu\text{tot}}$, will also increase with the feedback bits. In fact, it can be regarded that numerator of (4) multiplies $1/P_{\mu\text{tot}}$. Since the SE will not change with the feedback cycle, while $1/P_{\mu\text{tot}}$ reduces rapidly with the decrease of feedback cycle, the utility would change rapidly with small feedback cycle and it would reach the peak with fewer feedback bits.

Given a feedback cycle of 5ms, Figure 3 illustrates the effect of $\mu$ on the normalized EEFU. When $\mu=0$, the system only concerns SE and the normalized EEFU approaches the maximum value 1 as $B_{\text{sum}}$ becomes infinite. When $\mu=1$, the power consumption is important to the system and the maximum value of the utility is obtained when $B_{\text{sum}}=16$. Moreover, for $\mu=0.5$, the power consumption is also concerned in the system with less importance. Hence, the best performance is obtained at $B_{\text{sum}}=20$, where more feedback bits are employed compared to that with $\mu=1$.

Next, given a feedback cycle of 5ms and $\mu=1$, Figure 4 shows the bit allocation among the three cooperating BSs according to (12) that maximizes the unified EEFU. It can be seen that when $B_{\text{sum}}$ is small, all bits will be allocated to the closest BS since it can provide a higher received SNR. As $B_{\text{sum}}$ increases, the benefit of cooperation appears and some feedback bits should be allocated to further BSs.

Compared to Fig. 2, a pico BS is used to substitute closest macro BS in Figure 5. Since the pico BS has a lower transmitting power, it can be equivalent to a macro BS with higher power but placed further away. Different to Figure 4, the benefit of cooperation with two distant macro BSs will occur at a smaller number of feedback bits in Figure 5.
Using the same setting as in Figure 5, Figure 6 illustrates the system performance with MMSE and MRT precoding. The performance of MMSE is better than MRT with small number of feedback bits, while the performance of both precoders coincide with each other when a big number is considered. This is because CDI quantization errors of MMSE precoding are diminished cooperatively among three BSs by the joint design of precoding and decoding matrix at the expense of computation complexity. On the other hand, increase of feedback bits would make the CDI quantization of MRT more precise and help the two precoding methods achieve the same EEFU. Therefore, the MRT precoding method would be a better choice if there are sufficient feedback bits due to its simplicity. But when the number of feedback bits is small, MMSE could be chosen to provide better performance at the cost of higher complexity.

5. Conclusions

In this paper, we study the EEFU for CoMP networks and propose the utility function. The function can be applied for measuring the cost paid for feedback energy consumption and the benefits of SE gains. By adjusting utility coefficient, different application demands can be met with the EEFU function. It has been discovered that besides the number of feedback bits, the optimization of the function also relies on different environmental parameters aiming at different precoding methods. For instance, the optimization of EEFU relies on the transmission energy and distance of BSs for MRT precoding while feedback bits are equally allocated among BSs for MMSE precoding. The simulation results show that the optimization allows CoMP networks to take advantage of the feedback energy of MS much more efficiently. We mainly study the single-MS CoMP networks in this paper, and in the next step, studies will be conducted for more MSs scenarios.

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