Terminal-based Dynamic Clustering Algorithm in Multi-Cell Cellular System

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Abstract

A terminal-based dynamic clustering algorithm is proposed in a multi-cell scenario, where the user could select the cooperative BSs from the predetermined static base stations (BSs) set based on dynamic channel condition. First, the user transmission rate is derived based on linear precoding and per-cell feedback scheme. Then, the dynamic clustering algorithm can be implemented based on two criteria: (a) the transmission rate should meet the user requirement for quality of service (QoS); (b) the rate increment exceeds the predetermined constant threshold. By adopting random vector quantization (RVQ), the optimized number of cooperative BSs and the corresponding channel conditions are presented respectively. Numerical results are given and show that the performance of the proposed method can improve the system resources utilization effectively.

Keywords: dynamic clustering, multi-cell scenarios, per-cell feedback, random vector quantization

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1. Introduction

Multi-cell processing (MCP) is able to transform the undesirable ICI into useful signals via collaborative transmission [1]. Base Stations (BSs) need to share full data information and channel state information and form a distributed antenna array deployed among multiple cells. It is required that the cooperative BSs are linked by high-capacity delay-free links [2]. However, the backhaul capacity and feedback bandwidth are limited in a realistic cellular system [3]. Hence, the number of cooperative BSs should be limited. And how to select the cooperative BSs based on the channel state information in the cooperation set is critical for practical system design.

The cooperative BSs selection algorithms can be mainly grouped into two categories: static clustering and dynamic clustering [4][5]. For static clustering, the cooperative BSs are predetermined and do not change over time [6][7][8]. For dynamic clustering, cooperative BSs are expected to change over time based on channel state information [9][10]. In MCP systems, it is quite common to have non-uniform path losses between user and the cooperating BSs [11]. Therefore, the system resource can be utilized more effectively with dynamic clustering. In general, compared with static clustering, the dynamic approach usually has better performance due to larger optimizing domain.

In [12], dynamic clustering is formulated as a problem of total power minimization for target SINR. [13] presented a novel dynamic greedy algorithm for the formation of the clusters of cooperative BSs. In [14], the dynamic clustering control is adaptive to the global queue state information (GQSI). In the above researches, dynamic cooperative BSs selection algorithms are all operated at the base station controller (BSC). And dynamic clustering was transformed to be an optimization problem and discussed based on ideal CSI. However, full CSI cannot be obtained by the BSC in practical, especially for FDD system [15].

In this paper, we propose a terminal-based dynamic clustering algorithm from predetermined static clustering in multi-cell scenarios. Compared to select the cooperative BSs by the BSC directly, the user can provide the BSC more choices since more accurate channel information can be obtained at the terminal. First, the user transmission rate is derived based on the per-cell fixed feedback scheme and joint processing linear precoding scheme. And then, two criteria are presented to select the cooperative BSs: (a) whether the user rate requirement is satisfied; (b) whether the rate increment exceeds a pre*d*etermined constant threshold. The purpose of criterion (a) is to obtain the minimal number of BS to meet the user requirement for QoS; while criterion (b) aims to get the transmission rate as much as possible but the rate increment by adding one BS should not be negligible. The BSs far from the user will be excluded from the cooperative BSs set since just negligible rate increment is provided. Besides, the feedback overhead is reduced because the quantized channel information of the excluded BS is not necessary. Herein, the main contributions of this paper are as follows:

(a) A terminal-based dynamic clustering algorithm is proposed in multi-cell scenarios. Based on network configuration, a static cluster has been predetermined. Then, cooperative BSs are chosen from the static set according to dynamic channel condition.

(b) The transmission rate with limited feedback is derived. The per-cell feedback scheme is designed to maximize the transmission rate.

(c) Two cooperative BSs selection criteria are presented. And the optimization number of cooperative BSs and the corresponding channel conditions based on two different criteria are presented respectively.

The remainder of this paper is organized as follows. In Section 2, we present the system model and limited feedback mechanism. In Section 3, dynamic clustering algorithm is described in detail, and the optimization number of cooperative BSs based on two cooperative BSs selection criteria are presented respectively. Section 4 presents simulation results and conclusions are drawn in Section 5 finally.

2. System Model

2.1 Multi-Cell Channel Model

A downlink multi-cell scenario is considered where cooperative BSs are required to be selected from the pre-specified static cluster, which is illustrated as Fig.1.

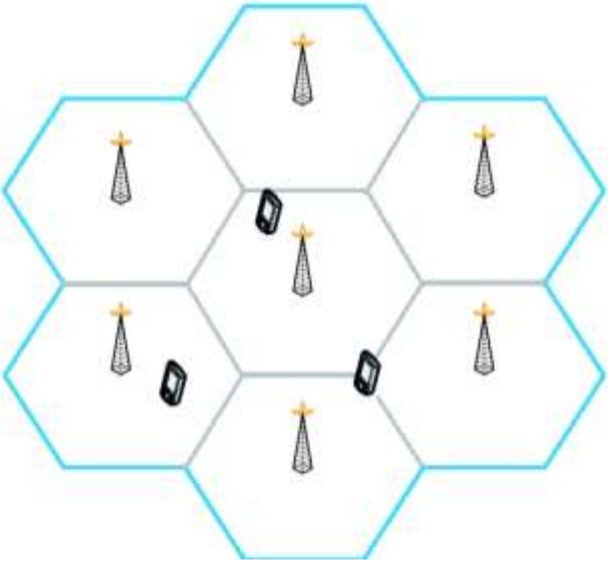

Fig. 1. A predetermined static clustering in multi-cell scenarios

Suppose that the static cluster includes N BSs each equipped with M antennas and the user is equipped with single antenna for simplicity. Independent flat-fading channel is considered. Then the channel vector between the BS$_j$ and the user is denoted as $\mathbf{h}_j$ ($j \in \{1,\ldots,N\}$), which corresponds to the small scale channel. And the aggregate channel constructed by K cooperative BSs can be given by:

$$\mathbf{h}_{agg\_K}^T = \left[\sqrt{g_1}\mathbf{h}_1^T \quad \sqrt{g_2}\mathbf{h}_2^T \quad \cdots \quad \sqrt{g_K}\mathbf{h}_K^T\right], \tag{1}$$

where K is the number of cooperative BSs ($K \in \{1,\ldots,N\}$), g_j denotes the large scale channel fading between the BS$_j$ and the user and the square root of gj presents the corresponding channel coefficient. We order the channel index by the large scale channel fading, i.e., $g_1 \geq g_2 \geq \ldots \geq g_K \geq 0$. Then, $\mathbf{h}_1$ represents the channel vector between the local BS and the user. In the practical multi-user transmission mode, the co-channel user is usually transparent and cannot by observed. Therefore, the cooperative BSs selection algorithm at the UE terminate is operated based on single user joint transmission mode. The BS or BSC will reselect the transmission mode and design the precoding according to the feedback information and system load balance. Under the assumption of K cooperative BSs and linear precoding, the received signal y could be formulated as follows:

$$y = \mathbf{h}_{agg\_K}^{T} \mathbf{w}_{agg\_K} x + n, \tag{2}$$

where x denotes the data symbol intended for the user, n is the complex white Gaussian noise with mean zero and variance δ^2, and $\mathbf{w}_{agg\_K}$ is denoted as the linear precoding vector which is constructed by the K received per-cell codebook vectors:

$$\mathbf{w}_{agg\_K} = \begin{bmatrix} \mathbf{w}_1^T & \mathbf{w}_2^T & \cdots & \mathbf{w}_K^T \end{bmatrix}^T, \tag{3}$$

where $\mathbf{w}_j$ denotes the precoding vector at the BS$_j$. The received effective SNR γ is described as follows:

$$\gamma_K = \frac{\left| \mathbf{h}_{agg\_K}^{T} \mathbf{w}_{agg\_K} \right|^2}{\sigma^2}. \tag{4}$$

The transmission rate with K cooperative BSs could be formulated as [16]:

$$C_K = \log_2 \left(1 + \gamma_K \right). \tag{5}$$

2.2 Limited Feedback

As discussed in the above subsection, the aggregate linear precoding is constructed based on the per-cell product codebook [17]. The user has a corresponding codebook $\mathcal{W}_i$ for each BS$_j$ in the static cluster and each codebook comprises 2^B quantization vectors. Here, B is the number of feedback bits for per BS. Random codebooks are assumed to be used here [18]. Note that each BS is assumed to use a different and independently generated quantization codebook; if a common codebook was used, there would be a non-zero probability that the user has the same precoding vector as different BSs, which reduces the number of spatial dimensions available [19].

Each code word is the preceding vector of the corresponding BS. The codewords are selected jointly to maximize the effective SNR (ESNR, γ). Mathematically, the aggregate precoding construction can be modeled as the following optimization problem:

$$\begin{cases} \max\limits_{\mathbf{w}_1, \mathbf{w}_2, \cdots, \mathbf{w}_K} \dfrac{\left| \mathbf{h}_{agg\_K}^{T} \begin{bmatrix} \mathbf{w}_1^T & \mathbf{w}_2^T & \cdots & \mathbf{w}_K^T \end{bmatrix}^T \right|^2}{\sigma^2} \\ \text{s.t.} \quad \mathbf{w}_k \in \mathcal{W}_k, k = 1, 2 \cdots K \end{cases}. \tag{6}$$

Once the aggregate precoding vector for the K dynamic cooperative BSs is obtained, the total number of feedback bits is definite, $B_{total} = BK$.

3. Dynamic Clustering Algorthm

In this section, the terminal-based dynamic clustering algorithm is described in detail. First, the user estimates the channel information from all the BSs in the static cluster to the terminate. And then the quantized joint precoding vector of different cooperative BSs set can be constructed to maximize the ESNR. The transmission rates based on different cooperative BSs set can be derived according to (5) utilizing the joint linear precoding scheme. Since the transmission rates could be known, the cooperative BSs could be selected to make better use of the system resource. Two dynamic clustering criteria are proposed to select the cooperative BSs: (a) the transmission rate satisfies the user requirement, i.e., $C_K \geq R$; (b) the rate increment exceeds a predetermined constant threshold Δ_R, i.e., $C_{K+1} - C_K \geq \Delta_R$. The BSs far from the user will be excluded from the cooperative BSs set since just negligible rate increment is provided. The outline of dynamic clustering algorithm is presented in **Algorithm 1**. And the optimal number of cooperative BSs based on the proposed criteria are presented respectively in *Theorem 1* and *Theorem 2*.

Algorithm 1: Dynamic clustering algorithm

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Step 1: The user estimates all the channel vectors $\mathbf{h}_k$ from the BSs to the user in the static cluster, $k \in \{1, \ldots, N\}$.
Step 2: The channel index is ordered by the large scale channel fading, $g_1 \geq g_2 \geq \cdots \geq g_K$.
Step 3: Construct the aggregate channel with $K$ cooperative BSs $\mathbf{h}_{agg\_K}^T$, $K \in \{1, \ldots, N\}$.
Step 4: Joint quantized linear precoding vector is constructed based on ESNR maximization (6).
Step 5: Based on the aggregate channel $\mathbf{h}_{agg\_K}^T$ and the linear precoding vector $\mathbf{w}_{agg\_K}$, the
        transmission rate $C_K$ is derived according to (5).
Step 6: Two criteria are presented to select the cooperative BSs: $C_K \geq R$ or $C_{K+1} - C_K \geq \Delta_R$. If the
        predetermined criterion is satisfied, the progress is finished; If not satisfied, set $K = K + 1$ and
        go to step 3 to repeat the progress. Note that $K$ is initially set to be 1.
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Theorem 1: When Criterion 1 is utilized in the dynamic clustering algorithm, i.e., the transmission rate is required to meet the user rate requirement ($C_K \geq R$), the optimal number of cooperative BSs is:

$$K = \left\lceil \frac{2^R - 1}{P_K v_K} \right\rceil, \tag{7}$$

where $P_K = \left(\sum_{k=1}^{K} g_k \left\| \mathbf{h}_k \right\|^2 / \delta^2 \right)$ denotes the SNR without quantization errors from the K cooperative BSs to the user, and $v_K = \left(1 - 2^{KB} \beta \left(2^{KB}, \frac{KM}{KM-1} \right) \right)$. Here we use $\beta(\cdot)$ to denote the beta function which is defined in terms of the gamma function as $\beta(x, y) = \frac{\Gamma(x)\Gamma(y)}{\Gamma(x+y)}$ [20].

When $K = 1$, it means that the cluster just includes the local BS and the transmission rate with the local BS satisfying the user requirement ($C_K \geq R$); When several BSs are included in the cluster, the following conditions should be satisfied:

$$\begin{cases} \rho_K \geq \dfrac{2^R - 1}{K v_K} - P_{K-1} \\[2ex] \rho_{K-1} < \dfrac{2^R - 1}{(K-1) v_{K-1}} - P_{K-2} \end{cases}, \quad 2 \leq K \leq N, \tag{8}$$

where $\rho_K = g_k \left\| \mathbf{h}_k \right\|^2 / \delta^2$ denotes the SNR without quantization errors from the K th cooperative BS to the user, and P_0 is set to be zero. Note that if the above conditions are not satisfied, i.e., $C_N < R$, the dynamic cluster does not exist. In this case, the user rate requirement cannot be satisfied even if all the BSs serve the user together.

Proof: We assume K is the optimal number of cooperative BSs, which is the minimal number of cooperative BSs satisfying the rate requirement. Then, the following condition can be given by:

$$\begin{cases} C_K \geq R \\ C_{K-1} < R \end{cases}, \ 1 \leq K \leq N, \tag{9}$$

where $C_{K\text{-}1}$ is set to be zero when $K = 1$. The user transmission rate can be rewritten as the following form:

$$\begin{aligned} C_K &= \log_2\left(1 + K\left(\sum_{k=1}^{K} \rho_k \left\|\mathbf{h}_k\right\|^2\right)\left|\tilde{\mathbf{h}}_{agg\_K}^T \tilde{\mathbf{w}}_{agg\_K}\right|^2\right), \\ &= \log_2\left(1 + KP_K \left|\tilde{\mathbf{h}}_{agg\_K}^T \tilde{\mathbf{w}}_{agg\_K}\right|^2\right) \end{aligned} \tag{10}$$

where $\tilde{\mathbf{h}}_{agg\_K}$ and $\tilde{\mathbf{w}}_{agg\_K}$ are the normalized aggregate channel vector and normalized aggregate precoding vector. The random codebook with $B_{total} = KB$ quantizing bits is applied in this system, and the expectation of the term $\left|\tilde{\mathbf{h}}_{agg\_K}^{\mathrm{T}} \tilde{\mathbf{w}}_{agg\_K}\right|^2$ can been formulated as the following closed form [21]:

$$E\left\{\left|\tilde{\mathbf{h}}_{agg\_K}^{\mathrm{T}} \tilde{\mathbf{w}}_{agg\_K}\right|^2\right\} = \left(1 - 2^{KB} \beta\left(2^{KB}, \frac{KM}{KM-1}\right)\right). \tag{11}$$

Then the transmission rate can be approximated based on the expectation of the term $\left|\tilde{\mathbf{h}}_{agg\_K}^{\mathrm{T}} \tilde{\mathbf{w}}_{agg\_K}\right|^2$:

$$\begin{aligned} C_K &\approx \log_2\left(1 + KP_K\left(1 - 2^{KB} \beta\left(2^{KB}, \frac{KM}{KM-1}\right)\right)\right), \\ &= \log_2\left(1 + KP_K v_K\right) \end{aligned} \tag{12}$$

where v_K represents the term $E\left\{\left|\tilde{\mathbf{h}}_{agg\_K}^{\mathrm{T}} \tilde{\mathbf{w}}_{agg\_K}\right|^2\right\}$. Substitute (12) into (9), the theorem can be proved.

Theorem 2: When Criterion 2 is utilized in the dynamic clustering algorithm, i.e., the rate increment exceeds a predetermined constant threshold $(C_K - C_{K-1} \geq \Delta_R, 1 \leq K \leq N)$, the optimal number of cooperative BSs is:

$$K = min\left(N, \left\lfloor \frac{2^{\Delta_R}\left(v_{K-1} - 1\right)}{\left(v_{K-1} 2^{\Delta_R} - v_K\right)} \right\rfloor\right). \tag{13}$$

And the following conditions should be satisfied:

$$\begin{cases} \rho_K \geq \dfrac{\left(1+(K-1)P_{K-1}v_{K-1}\right)2^{\Delta_R}-1}{Kv_K}-P_{K-1} \\ \\ \rho_{K+1} < \dfrac{\left(1+KP_Kv_K\right)2^{\Delta_R}-1}{(K+1)v_{K+1}}-P_K \end{cases} ,1 \leq K \leq N, \tag{14}$$

where ρ_{K+1} is defined as zero when $K=N$, which ensures the second inequality true.

Proof: Here K is assumed to be the optimal number of cooperative BSs, which is denoted as the maximal number of cooperative BSs satisfying the rate increment requirement. Then, the following conditions are presented similar to (9):

$$\begin{cases} C_K - C_{K-1} \geq \Delta_R \\ C_{K+1} - C_K < \Delta_R \end{cases} , \ 1 \leq K \leq N. \tag{15}$$

The rate increment term $\{C_{K+1} - C_K\}$ could be computed by substituting (12) into (15). If the rate increment term is larger than the threshold, continue to consider the next BS; If not, the cooperative BS set is determined. The optimal condition (14) could be obtained easily similar to *Theorem 1*.

Remark: When $\Delta_R \to \infty$, $K \to 1$. It implies that dynamic cluster just includes the local BS. While $\Delta_R \to 0$, $\left\lfloor \dfrac{2^{\Delta_R}(v_{K-1}-1)}{\left(v_{K-1}2^{\Delta_R}-v_K\right)} \right\rfloor \to \infty$, then $K=N$. In this case, all the BSs in the static cluster are selected to serve the user together. Note that criterion (a) is to obtain the minimal number of BS to meet the user requirement; while criterion (b) aims to get the transmission rate as much as possible but the rate increment by adding one BS should not be negligible.

4. Numerical Simulation

In this section, the transmission rate curves based on different cooperative BSs set are presented. Compared to per-cell feedback, the user performance with ideal channel feedback is also considered. In this simulation, it is assumed that the static cluster include five BSs. All the channel vectors from the BSs to user are flat fading Rayleigh channel. Random codebooks are assumed to be used because RVQ is very amenable to analysis and also performs measurably close to optimal quantization. Supposed that four bits are used to quantize the percoder for per BS. Note that each BS is assumed to adopt a different and independently generated quantization codebook.

In **Fig. 2**, the curves of user transmission rates with the number of cooperative BSs are given. Here, the SNRs from the BSs to the user are set to the same value, which corresponds to the cell edge user. The scenarios under both low SNR (10dB) and high SNR (20dB) conditions are considered in the simulation. From the simulation results, it can be seen that the transmission rate increases with the number of cooperative BSs since the BSs in the static cluster have the same impact on the use. **Fig. 3** and **Fig. 4** present the transmission rate with the number of cooperative BSs where the SNRs from the BSs to the user are different. Compared with the identical SNR scenario, the transmission rate increases slowly with the number of cooperative BSs. It implies that the cooperative BSs with lower SNRs have a weaker impact on the user transmission. In Fig. 4, the SNR step is very big, which corresponds to the inter-cell user. It can be easily seen that the local BS dominates the user performance. And as expected, there is the performance gap between the per-cell feedback and ideal feedback. Practical feedback scheme guarantees that the dynamic cluster algorithm can be operated with more accurate transmission rate.

Fig. 5 shows the transmission rates for different methods against the SNR. First it can be easily seen that cooperative communication with multiple BSs outperforms the traditional single cell transmission scheme much. In particular, the scheme with all BSs has the best performance since all the system resource has been used. By checking the special case with 3 cooperative BSs, we also could get that the proposed terminal-based dynamic clustering method outperforms the static clustering algorithm. This is because the best 3 BSs from the static BSs set are selected in our scheme, while in the static scheme 3 BSs are predetermined and no best performance is guaranteed.

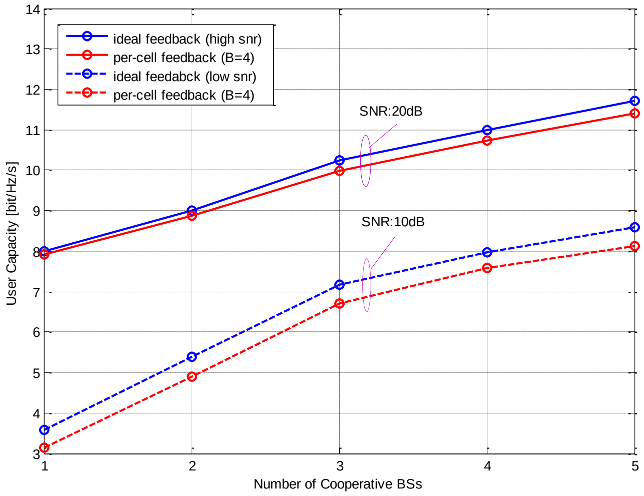

Fig. 2. The transmission rate performance for identical SNR scenarios

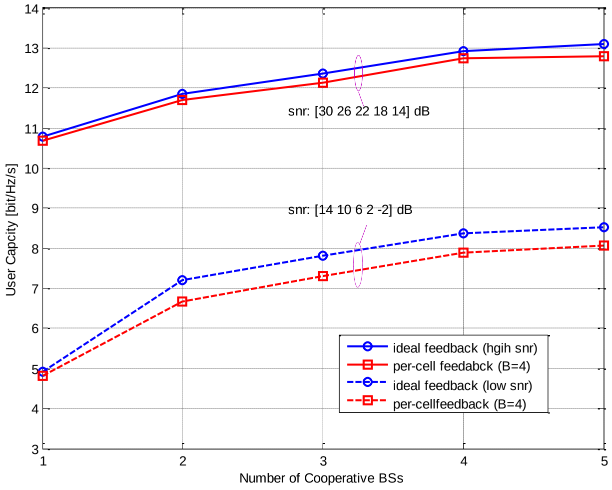

Fig. 3. The transmission rate performance for descending SNR scenarios

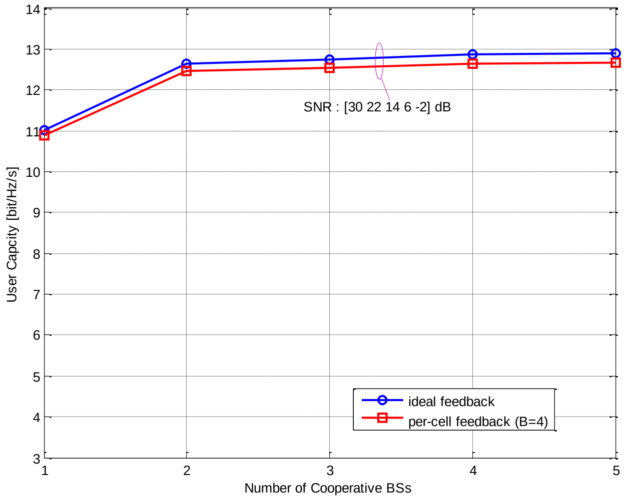

Fig. 4. The transmission rate performance for large SNR step scenarios

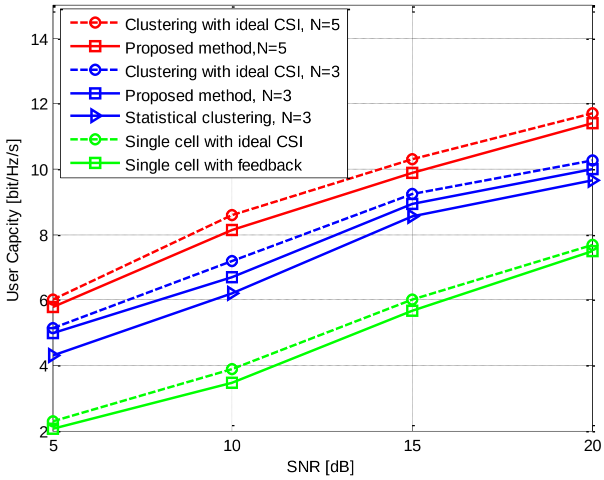

Fig. 5. The transmission rate performance against the SNR (B=4)

5. Conclusion

In this paper, a terminal-based dynamic clustering algorithm in multi-cell scenarios is proposed. The user could select the cooperative BSs from the predetermined static BSs set based on dynamic channel condition. Two criteria are presented to select the cooperative BSs: a) the user rate requirement is satisfied; b) the rate increment exceeds a predetermined constant threshold. Note that criterion (a) is to obtain the minimal number of BS to meet the user requirement; while criterion (b) aims to get the transmission rate as much as possible but the rate increment by adding one BS should not be negligible. The optimization number of cooperative BSs and corresponding channel conditions based on two cooperative BSs selection criteria are given respectively. The system resource can be utilized more effectively with dynamic clustering.

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