Tradeoff between Energy-Efficiency and Spectral-Efficiency by Cooperative Rate Splitting

Chungang Yang, Jian Yue, Min Sheng, and Jiandong Li

Abstract: **The trend of an increasing demand for a high-quality user experience, coupled with a shortage of radio resources, has necessitated more advanced wireless techniques to cooperatively achieve the required quality-of-experience enhancement. In this study, we investigate the critical problem of rate splitting in heterogeneous cellular networks, where concurrent transmission, for instance, the coordinated multipoint transmission and reception of LTE-A systems, shows promise for improvement of network-wide capacity and the user experience. Unlike most current studies, which only deal with spectral efficiency enhancement, we implement an optimal rate splitting strategy to improve both spectral efficiency and energy efficiency by exploring and exploiting cooperation diversity. First, we introduce the motivation for our proposed algorithm, and then employ the typical cooperative bargaining game to formulate the problem. Next, we derive the best response function by analyzing the dual problem of the defined primal problem. The existence and uniqueness of the proposed cooperative bargaining equilibrium are proved, and more importantly, a distributed algorithm is designed to approach the optimal unique solution under mild conditions. Finally, numerical results show a performance improvement for our proposed distributed cooperative rate splitting algorithm.**

Index Terms: **Cooperative game, concurrent transmission, green communication, heterogeneous network, interference management.**

I. INTRODUCTION

Since its inception, the LTE standard has evolved significantly toward LTE-Advanced, in which numerous spectral efficiency and peak data rate improvements have been introduced and guaranteed by effective advanced techniques. Among those, it is worth mentioning the improved orthogonal frequency division multiple access (OFDMA) and multiple input multiple-output (MIMO) techniques (e.g., multiuser/3D/massive/cooperative MIMO), where cooperative MIMO is the technology prototype of coordinated multiple point transmission/reception. Owing to these techniques, the spectral efficiency of a point-to-point link in cellular networks s approaching, its theoretical limits, and with the forecasted explosion of data traffic, there is a need to increase the node density to further improve the network capacity in accordance with the three-dimensional cube introduced in [1].

Therefore, an alternative strategy is needed, which is implemented by a promising scheme that has been widely discussed, where low-power access nodes are overlaid within a macrocell, creating what is referred to as a heterogeneous network (HetNet) [2]. HetNets are regarded as a promising new technique for enhancing capacity and coverage. However, the interference problem is critical because of the co-channel deployment of multiple small cells overlying the macrocell to achieve a much higher spectral efficiency [3]. Also, multicell coexistence in HetNets improve the chances of achieving multicell cooperation and a distributed antenna system, which are new communication paradigms promising significant system capacity targeting intercell interference elimination [4].

Recently, cognitive radio-sparkled interference management and cooperation-based design have attracted wide attention from the academia and industry [5]–[10]. However, most previous studies focus on spectral efficiency enhancement and interference avoidance, and the energy efficiency aspect is largely ignored for HetNets, as pointed out recently in [5]. It is noteworthy that rapidly rising energy costs and increasingly rigid environmental standards have led to an emerging trend of addressing the energy efficiency aspect of wireless communication technologies. It is estimated that the population of small cells is expected to be around 100 million with 500 million mobile users in 2020. The power consumption of a small cell today is approximately 6–10 W, and it can be assumed that a small cell in 2020 will still consume approximately 5 W. Therefore, the 100 million small cells in 2020 will consume approximately 4.4 TWh, an extra 5% over and above the energy consumption of the existing base station infrastructure. Therefore, with respect to both financial and environmental aspects, reducing energy consumption has become an important way to increase the profitability of operators and improve the quality of the user experience.

The energy efficiency of wireless networks has been extensively studied from various perspectives, such as decoding policy, dynamic planning, and network cooperation [6], [7]. Specially, network cooperation has become an effective technique to improve energy efficiency [6], [7]. An energy-aware network planning scheme that can guarantee both the coverage and traffic requirements has been proposed to reduce the energy consumption through intercell cooperation [6]. In HetNets, smart multimode terminals can achieve multi-access gain by simultaneously combining transmissions over several multiple points through network cooperation. Designing a concurrent transmission strategy that incorporates energy efficiency is a fundamental issue that involves various approaches including network cooperation.

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Multi-access cooperation diversity by combining transmission via traffic control is utilized to improve the system energy efficiency.

Unlike most current studies, which deal only with spectral efficiency enhancement, we implement an optimal rate splitting strategy to improve both spectral efficiency and energy efficiency by exploring and exploiting cooperation diversity. The tradeoff between energy efficiency and spectral efficiency has attracted wide attention; for instance, [11] mathematically investigates the fundamental tradeoff between energy efficiency and spectral efficiency in downlink OFDM access networks; and [12] tells under which circumstances throughput and energy efficiency can be both jointly maximized and where they constitute different challenges in IEEE 802.11 WLANs. Meanwhile, rate splitting ends uses in [13] for interference mitigation in multicell wireless networks and in [14] for a multilayer rate splitting scheme in heterogeneous networks for improving the cell-edge user experience. However, both [13] and [14] neglect the issue of energy efficiency maximization while investigating rate splitting schemes.

Motivated by the popular cooperative game in the wireless community [16] and the distributed algorithm design for solving the cooperative game [17], we first introduce the motivation and rationale underlying our idea of a cooperative rate splitting design that achieves both energy efficiency and spectral efficiency. After illustrating the system model in Section II and using the typical cooperative bargaining cooperative game, we formulate the cooperative rate splitting problem in Section III. Then, we derive the best response function by analyzing the dual problem of the primal problem. Furthermore, the existence and uniqueness of the proposed cooperative bargaining equilibrium are proved in Section IV, and more importantly, a distributed algorithm is designed to approach the optimal unique solution under mild conditions in Section V. Numerical results presented in Section VI demonstrate the improved performance of our proposed algorithm, and we conclude the paper in Section VII.

II. SYSTEM MODEL AND RATIONALE OF OUR IDEA

In this section, we first illustrate the multicell cooperation HetNet system, and then we clarify the motivation and rationale underlying our idea of cooperative rate splitting for achieving both energy efficiency and spectral efficiency.

A. System Model

The considered multicell cooperation system is illustrated in Fig.1, where multiple types of base stations with different transmission powers and coverage coexist with each other. There are macrocell eNodeBs (MeNBs) and various smallcell eNBs (SeNBs), e.g., femtocell eNodeB (FeNB) and picocell eNodeB (PeNB). Meanwhile, different eNBs can exchange context information to achieve efficient cooperation. This contextual information includes user traffic information, channel status information, and residual energy information from the X2 interface or the optical/cable backhaul.

We only investigate the downlink case in this study, although the following analysis also applies to the uplink case. We assume that a large data requirement arises in a smart terminal equipped with multimode interfaces. We focus on the specific HetNets scenario with the same radio access technology, i.e., OFDMA.

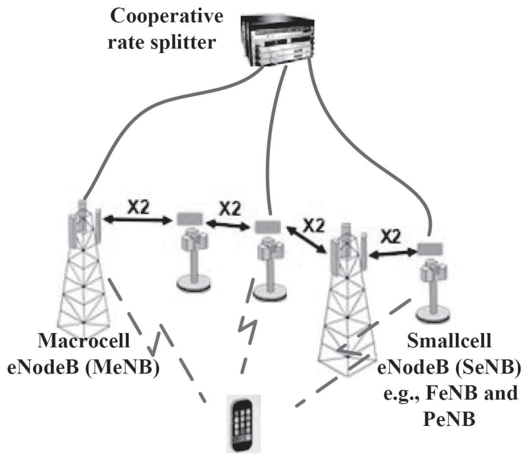


Fig. 1. HetNets with multicell concurrent transmission.

In the considered HetNets scenario with multicell concurrent transmission in Fig. 1, we investigate the problem of a large downlink traffic rate ρ; the cooperative rate splitter should determine the optimal concurrent rate $\rho_i^\star$ for each cooperating radio access network, i.e., RAN_i. Then, with the optimal rate splitting ratio $o_i^\star = \frac{\rho_i^\star}{\rho}$ determined, several specific RANs will cooperate to transmit the large traffic using a practical concurrent scheme. In this study, we use the terms RAN and player interchangeably because a RAN is the player in the cooperative game-theoretic formulations in the next sections.

B. Rationale of Our Idea

Without loss of generality, and under the framework of the Shannon formula, the theoretical traffic rate or spectrum efficiency ρ_i achieved by RAN_i can be approximately represented as

$$\rho_i = \omega_i \ln\left(1 + \frac{p_i}{\mu_i}\right) \tag{1}$$

where ω_i is the allocated bandwidth, p_i is the downlink transmission power, and μ_i represents the potentially normalized aggregate interference power from other cooperative RAN coalitions perceived by RAN_i. Here, we omit the RAN coalition formation process, the details of which can be found in the coalitional game-theoretic work [16], and here we only assume that there are N RANs formulating one multicell cooperation coalition. Therefore, mathematically, we compute the power consumed by RAN_i, which is

$$p_i = \mu_i\left(e^{\frac{\rho_i}{\omega_i}} - 1\right). \tag{2}$$

To measure the energy efficiency, we select the metric of (3) in the unit of nat/s/W, which is given by

$$\eta_i = \frac{\rho_i}{p_i + p_i^{\text{cst}}} \tag{3}$$

where p_i is the transmission power consumption. We denote the fixed power consumption of the circuit by p_i^{cst} following [10] and [11].

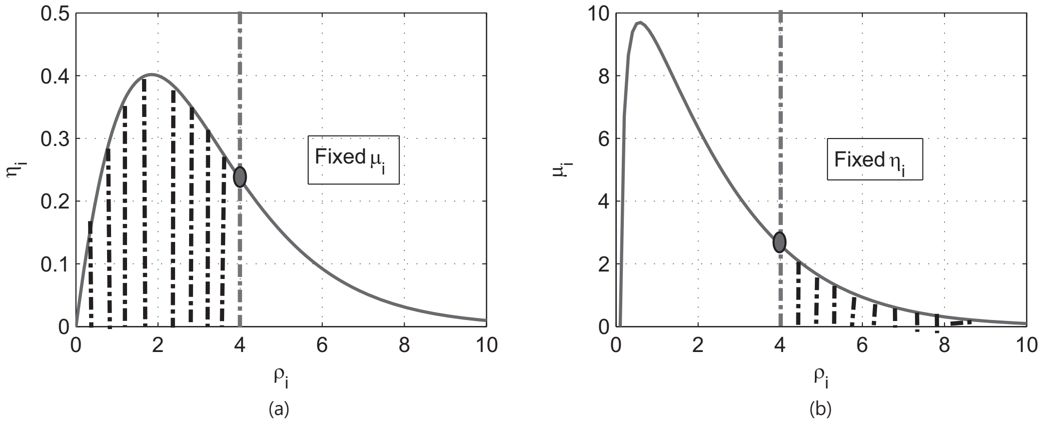


Fig. 2. Tradeoffs between energy efficiency and spectral efficiency with respect to the carried traffic rate: (a) Energy efficiency against the traffic rate with the fixed spectral efficiency and (b) spectral efficiency against the traffic rate with fixed energy efficiency.

The energy efficiency η_i of RAN_i is a measure of its attained traffic rate ρ_i with respect to the total consumed power $p_i + p_i^{\mathrm{cst}}$ for the wireless player. Typically, a player, i.e., the RAN_i, would like to achieve a high spectral efficiency while at the same time expending a small amount of energy. Thus, both spectral efficiency and transmit power are desirable for a wireless player. There exists a tradeoff between obtaining both high spectral efficiency and low energy consumption. Finding a good balance between these two conflicting objectives is the primary focus of this study.

Equation (3) has several implications, which are illustrated through the conceptual plot in Fig. 2. In fact, in this study, we omit the power control scheme design, which is a conventional technique to achieve both energy efficiency and spectral efficiency. Throughout this paper, the transmit power p_i of any specific RAN_i is assumed to be fixed; therefore, the perceived aggregate interference power μ_i dominates the spectral efficiency. This follows from (1). In other words, μ_i reflects the spectrum efficiency at the determined transmit power p_i well. It is noted that a higher interference power μ_i means a lower spectral efficiency, and a high spectral efficiency implies a lower interference power. In practical communication scenario, it's known that μ_i varies with the channel state and interference situation. However, to reflect the effect of the traffic rate ρ_i on both spectrum efficiency μ_i and energy efficiency η_i of RAN_i, we assume that the transmit power p_i is fixed during the following analysis, and therefore, μ_i dominates the spectral efficiency.

First, we assume that the perceived aggregate interference power μ_i has a fixed value; in other words, the spectral efficiency is fixed. Under this condition, we illustrate the plot of energy efficiency η_i against the carried traffic rate ρ_i, and the plot of energy efficiency against the traffic rate is depicted in Fig. 2(a). We can see that the energy efficiency first increases and then decreases as the carried traffic rate increases. If the energy efficiency η_i alone is considered, then the rational choice of traffic rate should be selected the point of $\rho_i = 2$. When the energy efficiency η_i is assumed to be fixed, the plot of spectral efficiency μ_i againt the traffic rate ρ_i as shown in Fig. 2(b). At this time, a high spectral efficiency is expected to be achieved, that is, a low interference power μ_i, because a higher interference power μ_i implies a lower spectral efficiency. Therefore, a much lower value should be selected for the traffic rate in order to obtain a higher spectral efficiency, e.g., after the point of $\rho_i = 2$, for instance, $\rho_i = 4$. In summary, $\rho_i = 4$ may be a good point for achieving the optimal tradeoff between energy efficiency and spectral efficiency. From above analysis, it is safe to conclude that every RAN has an optimal traffic rate choice. Therefore, the optimal rate splitting algorithm should be designed taking both the aggregate rate requirement and capabilities of the RAN into considerations.

III. COOPERATIVE RATE SPLITTING GAME

In this paper, we describe an optimal rate splitting scheme based on cooperative game theory, which guarantees the performance of both efficiency and fairness among different RANs in this cooperative coalition. There are N cooperating RANs, and the concerned RANs are interchangeably called players in this paper. Other tuples constituting the most popular game-theoretic model are the action set and the utility function.

It's now known that the optimal Nash cooperative bargaining solution (NBS)-based control will achieve an optimal tradeoff between Nash fairness and Nash axiomatic efficiency under the framework of Nash axiomatic theory, which has been verified in our previous NBS-formulated work of [16]. In summary, in the optimal bargaining solution (BS)-based rate splitting solution $(\rho_1^\star, \rho_2^\star)$ of a two-player cooperative rate splitting game, the cooperative rate splitting game (CRSG) can be achieved by solving the Nash-product problem of $(\rho_1^\star, \rho_2^\star) = \max_{\eta_1 \geq \eta_1^{\min}, \eta_2 \geq \eta_2^{\min}} (\eta_1 - \eta_1^{\min})(\eta_2 - \eta_2^{\min})$, where $\eta_1^{\min}$ and $\eta_2^{\min}$ are regarded as the disagreement points. Generally, $\eta_1^{\min}$ and $\eta_2^{\min}$ are set as the minimal energy efficiency requirements to guarantee achievement of the CRSG.

Definition 1: The N-player cooperative cognitive rate splitting game is formulated as CRSG $= \{\mathcal{N}, \mathcal{S}, \mathcal{U}\}$, with $\mathcal{N} = \{1, 2, \cdots, N\}$ as the player set, and N-RANs as players; $\mathcal{S}$ is the Cartesian product action space defined as $\mathcal{S} = \prod_{i=1}^{N} \mathcal{S}_i$, where $\mathcal{S}_i$ represents the available set of player i; $\mathcal{U}$ is utility function, which characterizes the player's preference regarding the tradeoff between energy efficiency and spectral efficiency.

In the general cooperative bargaining game-theoretic framework, the cooperative rate splitting game is formulated as the following optimization problem

$$\textbf{P1}: \quad \max \quad u=\prod_{i=1}^{N}\left(\eta_i-\eta_i^{\min}\right), \tag{4a}$$

$$\text{subject to} \quad \rho \le \sum_{i=1}^{N}\rho_i, \tag{4b}$$

$$\rho_i \le \rho_i^{\max}, i=1,\cdots,N \tag{4c}$$

where η_i and $\eta_i^{\min}$ are the spectral efficiency function defined in (3) and the minimum spectral efficiency for player i to join in the game, respectively. ρ represents the aggregate traffic rate towards the N cooperating players, ρ_i and $\rho_i^{\max}$ are the rate and maximum rate of player i, respectively. Objective (4a) is the Nash product function of the spectral efficiency function defined in (3) and the minimum spectral efficiency of player i, which is in line with Nash bargaining game-theoretic framework. Constraint (4b) requires that the rate splitting result allow the aggregate traffic rate towards the N cooperating players to be fully offloaded to them; moreover, each player is also constrained by the individual rate limit in (4c).

According to [16], the equivalent model of (4) is given by

$$\textbf{P2}: \quad \max \quad \hat{u}=\sum_{i=1}^{N}\log\frac{\rho_i}{\varphi_i(\rho_i)}, \tag{5a}$$

$$\text{subject to} \quad \varphi_i(\rho_i)=\mu_i\left(e^{\frac{\rho_i}{\omega_i}}-1\right)+p_i^{\text{cst}}, \tag{5b}$$

$$(4b) \quad \text{and} \quad (4c) \tag{5c}$$

with the minimum spectral efficiency of player i assumed to be $\eta_i^{\min}=0$. This equivalent re-formulation is widely used to transfer the Nash product-based objective function into the utility-summation form using the logarithmic function [16]. Without loss of generality, this process does not change the convexity of the primal objective function in (4).

IV. ANALYSIS

In this section, the dual problem of problem **P2** in (5) is first given, based on which we analyze the proposed cooperative rate splitting game and the solution properties.

A. The Dual Problem

In this section, we solve the problem **P2** in (5) by solving its dual problem, shown as

$$\textbf{P3}: \quad \max_{\lambda\ge 0,\kappa_i\ge 0, i\in\mathcal{N}} \quad \mathcal{L}, \tag{6a}$$

$$\text{subject to} \quad \rho_i\in\mathcal{S}_i, i\in\mathcal{N} \tag{6b}$$

where

$$\mathcal{S}_i=\left\{\rho\le\sum_{i=1}^{N}\rho_i, \rho_i\le\rho_i^{\max}, i\in N\right\} \tag{7}$$

and $\mathcal{L}$ represents the Lagrangian function associated with **P2**, which is given by

$$\begin{aligned}\mathcal{L} &= \sum_{i=1}^{N}\log\frac{\rho_i}{\varphi_i(\rho_i)}-\lambda\left(\rho-\sum_{i=1}^{N}\rho_i\right)-\sum_{i=1}^{N}\kappa_i\left(\rho_i-\rho_i^{\max}\right)\\ &= \sum_{i=1}^{N}\left(\log\frac{\rho_i}{\varphi_i(\rho_i)}+(\lambda-\kappa_i)\,\rho_i\right)+\delta\end{aligned} \tag{8}$$

where $\delta=\lambda\rho+\sum_{i=1}^{N}\left(\kappa_i\rho_i^{\max}\right)$, with the Lagrangian multipliers λ and $\kappa_i, i=1,\cdots,N$, introduced to relax (4b) and (4c).

It is easy to verify the problem **P2** in (5) is a convex optimization problem. Thus, the duality gap between this problem and its dual optimization problem is zero, and we can solve the primal problem by solving its dual problem.

Corollary 1: The dual gap between problem **P2** in (5) and the dual problem **P2** in (6) is zero.

Proof: We should prove that both the objective function and the available set are convex. First, from the properties of the objective function, we have

$$\begin{aligned}\hat{u} &= \sum_{i=1}^{N}\log\frac{\rho_i}{\varphi_i(\rho_i)}\\ &= \sum_{i=1}^{N}\left(\log\rho_i-\log\varphi_i(\rho_i)\right)\end{aligned} \tag{9}$$

where $\varphi_i(\rho_i)$ is convex with respect to ρ_i as shown in (5b), and logarithmic function does not change the convexity; therefore, $\log\varphi_i(\rho_i)$ still remains the convexity property, and further, we know that $\log\rho_i$ is also convex. In summary, the objective function is convex. We can thus concentrate on the convexity of the available set $\mathcal{S}_\rangle$ of player i. It is easy to see that (11) is convex, which combines the constraints (4b) and (4c).

B. Analysis of the Cooperative Rate Splitting Game

In the following, we first define the cooperative bargaining equilibrium solution (CBES) of the formulated cooperative rate splitting game and investigate its properties. We use the straightforwardly achieved definition in game theory to describe the equilibrium behaviors.

Definition 2: CBES. A rate splitting profile $\rho^\star=\{\rho_i^\star, i\in\mathcal{N}\}$ is a pure strategy CBES if and only if no player can improve its utility by deviating unilaterally, i.e.,

$$\hat{u}(\rho_i^\star,\rho_{-i}^\star)\ge\hat{u}(\rho_i,\rho_{-i}^\star), \forall i\in\mathcal{N}, \forall\rho_i\in\mathcal{S}_i, \rho_i\ne\rho_i^\star.$$

The CBES for the cooperative rate splitting game can be guaranteed by following best response function.

Definition 3: The best response function (BRF). We define the BRF of player $i\in\mathcal{N}$ as the rate splitting profile that maximizes the utility when any rate profiles $\{\rho_{-i}, -i\in\mathcal{N}, -i\ne i\}$ of other players are given. Mathematically, it is represented as

$$\hat{\pi}(\rho_{-i})=\arg\max_{\rho_i\in S_i}\hat{u}(\rho_i,\rho_{-i}).$$

Lemma 1: Based on the definition of the BRF, it's known that the cooperative bargaining equilibrium solution of player $i\in\mathcal{N}$

is

$$\rho_i^\star = \hat{\pi}(\rho_{-i}).$$

Therefore, it is critical to derive the detailed BRF for the cooperative rate splitting game considered in this paper.

Corollary 2: If the unified spectrum is shared by both MeNB and multiple SeNBs, that is $\omega_i = 1$, then the best response function of the defined game given by $\hat{\pi}(\rho_{-i}) = \frac{1}{\pi(\rho_{-i})}$, where $\pi(\rho_{-i}) = \frac{\varpi_i}{e^{\rho_i} - \varpi_i} - (\lambda - \kappa_i - 1)$, where $\varpi_i = 1 - \frac{p_{\rm cst}}{\mu_i}$, and λ and κ_i are the introducing parameters that are strongly related to the aggregated and individual transmit traffic rate constraints.

Proof: With respect to the transmit traffic rate ρ_i, we derive the first-order derivation of the Lagrangian relaxed function in (8), which yields

$$\begin{aligned} \frac{\partial \mathcal{L}}{\partial \rho_i} &= \log \frac{\rho_i}{\varphi_i(\rho_i)} + (\lambda - \kappa_i)\,\rho_i \\ &= \frac{\varphi_i(\rho_i)}{\rho_i} \frac{\varphi_i(\rho_i) - \rho_i \frac{\partial \varphi_i(\rho_i)}{\partial \rho_i}}{\varphi_i^2(\rho_i)} + (\lambda - \kappa_i) \\ &= \frac{1}{\rho_i} - \frac{1}{\varphi_i(\rho_i)} \frac{\partial \varphi_i(\rho_i)}{\partial \rho_i} + (\lambda - \kappa_i) \end{aligned} \tag{10}$$

where

$$\begin{aligned} \frac{\partial \varphi_i(\rho_i)}{\partial \rho_i} &= \frac{\mu_i}{\omega_i} e^{\frac{\rho_i}{\omega_i}} \\ &= \frac{\varphi_i(\rho_i) + \mu_i - p_i^{\rm cst}}{\omega_i}. \end{aligned} \tag{11}$$

Therefore, (10) is

$$\begin{aligned} \frac{\partial \mathcal{L}}{\partial \rho_i} &= \frac{1}{\rho_i} - \frac{1}{\varphi_i(\rho_i)} \frac{\partial \varphi_i(\rho_i)}{\partial \rho_i} + (\lambda - \kappa_i) \qquad (12)\\ &= \frac{1}{\rho_i} - \frac{1}{\varphi_i(\rho_i)} \left(\frac{\varphi_i(\rho_i) + \mu_i - p_i^{\rm cst}}{\omega_i} \right) + (\lambda - \kappa_i)\,. \end{aligned}$$

If the unified spectrum is shared by both MeNB and multiple SeNBs, that is $\omega_i = 1$, then let

$$\frac{\partial \mathcal{L}_\rangle}{\partial \rho_i} = \frac{1}{\rho_i} - \frac{\varpi_i}{e^{\rho_i} - \varpi_i} + (\lambda - \kappa_i - 1) = 0, \tag{13}$$

we then have

$$\frac{1}{\rho_i} = \frac{\varpi_i}{e^{\rho_i} - \varpi_i} - (\lambda - \kappa_i - 1) = \pi(\rho_{-i}). \tag{14}$$

Therefore, from the definition of the BRF in Definition 2 and Lemma 1, one can conclude that

$$\rho_i{}^\star = \frac{1}{\pi(\rho_{-i})} = \hat{\pi}(\rho_{-i}). \tag{15}$$

This concludes the proof.

C. Existence and Uniqueness

Having obtained the BRF, we next prove its convergence and uniqueness. If we want to certify that the BRF iteration $\rho_i^{t+1} = \frac{1}{\pi(\rho_{-i}^t)}$ of the player i converges to a fixed and unique point, the BRF iteration of player i should have the following properties [15]:

- Positivity: $\pi(\rho_{-i}) > 0$.
- Inverse monotonicity: If $\rho_i^1 \geq \rho_i^2$, then $\pi(\rho_{-i}^1) \leq \pi(\rho_{-i}^2)$.
- Scalability: If $\varrho > 1$, then $\varrho\pi(\rho_{-i}) > \pi(\varrho\rho_{-i})$.

Remark 1: Note that the Positivity indicates the feasibility of the rate splitting scheme. Inverse monotonicity reflects the cooperation behavior between player i with its opponents $-i \in \mathcal{N}, -i \neq i$, which means that increasing the rate of the player 1 results in decreasing the rate of the player 2. Scalability ensures that the rate variations achieved by other players $-i \in \mathcal{N}, -i \neq i$ will always be smaller than that achieved by player i, which guarantees the rationality and convergence property of the iterations.

Corollary 3: The convergence and uniqueness of the BRF of player i can be guaranteed if and only if $\rho_i < \log\left(\frac{\lambda - \kappa_i}{\lambda - \kappa_i - 1}\varpi_i\right)$.

Proof: We now prove the Positivity, Inverse monotonicity, and Scalability properties.

(1) Positivity: From the detailed form of BRF in Corollary 2, with respect to Positivity, we can obtain

$$\frac{e^{\rho_i}}{\varpi_i} < \frac{\lambda - \kappa_i}{\lambda - \kappa_i - 1} \tag{16}$$

and further,

$$\rho_i < \log\left(\frac{\lambda - \kappa_i}{\lambda - \kappa_i - 1}\varpi_i\right). \tag{17}$$

(2) Inverse monotonicity: We can see that the detailed form of BRF in Corollary 2 is a decreasing function with respect to ρ_i; therefore if $\rho_i^1 \geq \rho_i^2$, then $\pi(\rho_i^1) \leq \pi(\rho_i^2)$, which always holds.

(3) Scalability: If $\varrho > 1$, then we have (18). Then $\pi(\varrho\rho_i) - \varrho\pi(\rho_i) < 0$ always holds, which concludes the proof.

Corollary 4: (Existence) A CBES always exists in the game.

Proof: To prove the existence property, we compute the the second-order differential function, which is given by

$$\frac{\partial^2 \mathcal{L}_i}{\partial^2 \rho_i} = \frac{e^{\rho_i}}{\left(e^{\rho_i} - \varpi_i\right)^2}\varpi_i - \frac{1}{\rho_i^2}$$

where $p_{\rm cst} > \mu_i$ always holds for a practical system; therefore, $\varpi_i = 1 - \frac{p_{\rm cst}}{\mu_i} < 0$ holds. It is easy to see that $\frac{e^{\rho_i}}{(e^{\rho_i} - \varpi_i)^2} > 0$ and $\frac{1}{\rho_i^2} > 0$; therefore, we can conclude that $\frac{\partial^2 \mathcal{L}_i}{\partial^2 \rho_i} < 0$. Thus, there always exists at least one equilibrium solution for the formulated game model.

V. DISTRIBUTED COOPERATIVE RATE SPLITTING ALGORITHM

In this section, a distributed cooperative rate splitting algorithm is presented to achieve the optimal bearer of each RAN$_i$, $i \in \mathcal{N}$.

- Initialization: Initialize the related parameters including the fixed power consumption $p_{\rm cst}$ and the introduced Lagrangian factors of λ^0 , κ_i^0 of the player $i \in \mathcal{N}$.
- Observation: Compute the channel fading information according to the feedback information and location information, and employ the potential interference power information μ_i, to achieve the environment awareness and fully exploit the cooperative gains. Finally, these all yield the complete information of $\varpi_i = 1 - \frac{p_{\rm cst}}{\mu_i}$.

$$\begin{aligned}\pi(\varrho\rho_i) - \varrho\pi(\rho_i) &= \frac{\varpi_i}{e^{\frac{\varrho\rho_i}{\omega_i}} - \varpi_i} - (\lambda - \kappa_i - 1) - \varrho\left(\frac{\varpi_i}{e^{\frac{\rho_i}{\omega_i}} - \varpi_i} - (\lambda - \kappa_i - 1)\right) \\ &= \frac{\varpi_i}{e^{\frac{\varrho\rho_i}{\omega_i}} - \varpi_i} - \varrho\frac{\varpi_i}{e^{\frac{\rho_i}{\omega_i}} - \varpi_i} - (1-\rho)(\lambda - \kappa_i - 1)\end{aligned} \tag{18}$$

- Decision: Repeat the following steps:
  - First, compute the best response function of

$$\pi(\rho_i^t) = \frac{\varpi_i}{e^{\rho_i} - \varpi_i} - (\lambda^t - \kappa_i^t - 1).$$

  - Achieve the next rate variable of

$$\rho_i^{t+1} = \frac{1}{\pi(\rho_i^t)}.$$

  - Update the Lagrangian multipliers using

$$\lambda^{t+1} = \lambda^t + \alpha\left(\rho - \sum_{i=1}^{N}\rho_i^t\right) \tag{19}$$

and

$$\kappa_i^{t+1} = \kappa_i^t + \beta\left(\rho_i^t - \rho_i^{\max}\right) \tag{20}$$

where α and β are the adjustable step factors, which affect the convergence properties.

- Conclusion: Determine the termination condition using

$$\left\|\lambda^{t+1} - \lambda^t\right\| \le \varepsilon_1$$

and

$$\left\|\kappa_i^{t+1} - \kappa_i^t\right\| \le \varepsilon_2$$

where ε_1 and ε_2 are convergence precision settings.

Remark 2: Here, the iteration equations of the Lagrangian multipliers (19) and (20) are achieved by the subgradient derivations.

VI. NUMERICAL RESULTS

In this section, we first illustrate the simulation scenarios and the basic settings with detailed parameters. Then, we verify the convergence property, the effectiveness condition, and the improved performance of the proposed distributed cooperative rate splitting (DCRS) scheme. Finally, we evaluate the scheme with more extensive settings, including the interference situation, different requirements, and multiple players.

A. Simulation Settings

In this section, we present simulation results for an interference-limited downlink OFDMA heterogeneous network and observe the performance of the proposed algorithm in equilibrium. The heterogeneous network consists three types of eNodeB, including FeNB and PeNB, both of which underlay in the coverage of MeNB, shown in Fig. 3.

In Fig. 3, we concentrate on performance verification of the multimode user equipment (MUE), where the MUE_1 has selected the FeNB and PeNB to form the concurrent links. Also, the MUE receives the interference power from other downlink eNBs, for instance, the MeNB, in the considered scenario. Each eNB achieves the backhaul link. We omit the details of the selection scheme here, but the assumption is that each MUE always can achieve the best choice of the concurrent links. The system parameters are listed in Table 1.

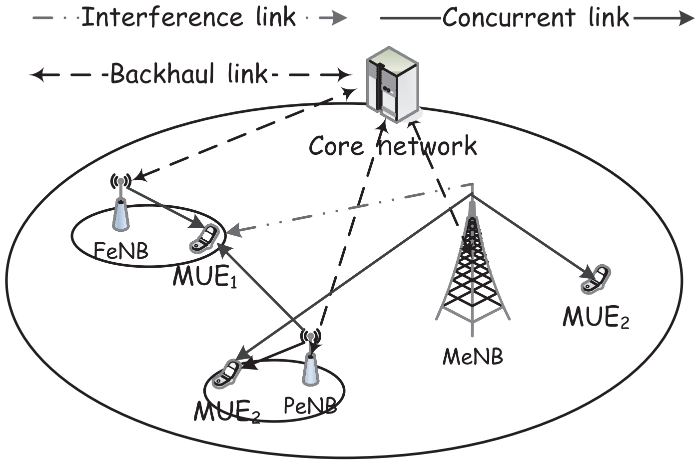


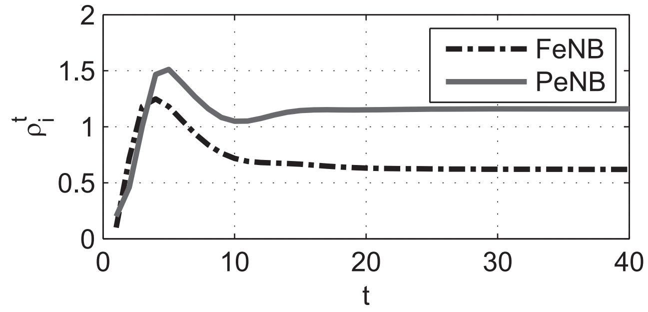
Fig. 3. A typical simulation scenario with multiple types of smallcells.

Table 1. System simulation parameters.

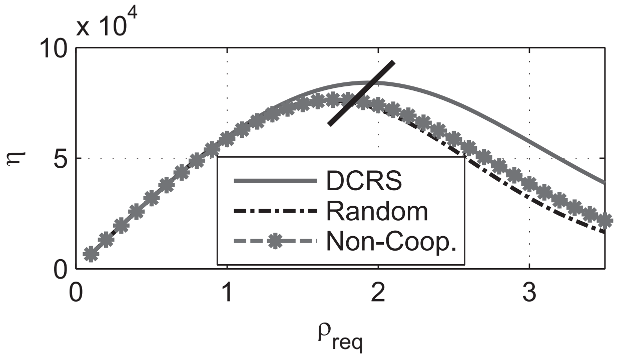
Simulation Parameter	Value
Bandwidth	Normalized spectrum and co-channel deployment
Transmission power	Each eNodeB employs fixed power: $P_{\text{MeNB}} = 46$ dBm, $P_{\text{PeNB}} = 30$ dBm and $P_{\text{FeNB}} = 20$ dBm
Maximum rate bearer	$\rho_{\text{PeNB}} = 10$ Mbps $\rho_{\text{PeNB}} = 5$ Mbps
Channel fading model	MUE $\leftrightarrow$ MeNB $= 15.3 + 37.6\log_{10} d$ MUE $\leftrightarrow$ PeNB $= 140.7 + 36.7\log_{10} d$ MUE $\leftrightarrow$ FeNB $= 38.4 + 20\log_{10} d$

B. Initial Verification

First, we simulate the iteration process of of the propped DCRS scheme, where we assume that the total rate requirement $\rho = 1.8$ Mbps of MUE_1, and the maximum carried traffic rates of the associated FeNB and PeNB are 1 Mbps and 1.5 Mbps, respectively. Either FeNB or PeNB can meet the huge rate requirement, and they have to cooperatively transmit concurrently by optimally splitting the traffic rate between them. Then, from Fig. 4(a), we can see that the proposed DCRS algorithm always quickly converges to 0.6144 for FeNB and 1.1856 for PeNB, in



(a)



(b)

Fig. 4. (a) Convergence verification and (b) Effectiveness condition of the DCRS scheme.

about 20 iterations (on the order of milliseconds). Finally, employing the splitting ratio of $\frac{0.6144}{1.8}$ and $\frac{1.1856}{1.8}$ can guarantee the downlink rate requirements concurrently transmitted by the FeNB and PeNB.

The proposed DCRS scheme is a cooperative scheme, and we use the non-cooperative (Non-Coop.) and random (Random) schemes as the benchmarks. These schemes involved in the simulations, including the proposed DCRS, the Non-Coop. and the Random, are all distributed schemas. Therefore, we omit a comparison of the signaling overhead, for instance, with the centralized scheme. First, it is noted that these schemes will work more effectively when the specific rate requirements are large enough, as shown in 4(b). This conclusion is evident because, for example, if the total rate $\rho_{\rm req}$ is small, the rate splitting is not helpful for increasing the energy efficiency. A single RAN provides an acceptable rate guarantee for small requirements.

Second, compared to the typical benchmark algorithm of Non-Coop., we show an improved performance for the proposed DCRS scheme in Fig. 5. The ratio of the interference to the energy efficiency μ/η is plotted on the x-axis; in other words, it is the ratio of the spectral efficiency and the energy efficiency, the cumulative distribution function (CDF) of which shows that our proposed DCRS algorithm can achieve a better tradeoff between them.

C. Further Performance Evaluation

Finally, we evaluate the proposed scheme with more extensive settings, including the interference situations $5e-8 \sim 5e-7$, different requirements, $\rho_{\rm req} = 0.1$ Mbps $\sim$ 3.5 Mbps, and multiple players, $N = 4, 6, 8, \text{and } 10$. In addition, to reflect the

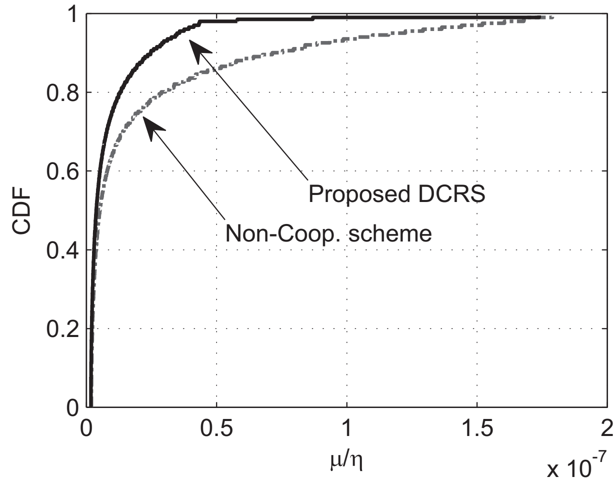
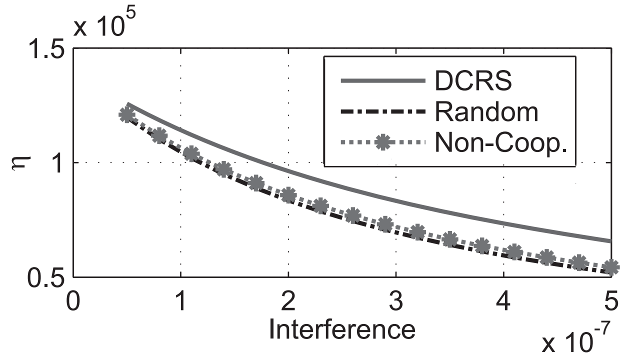
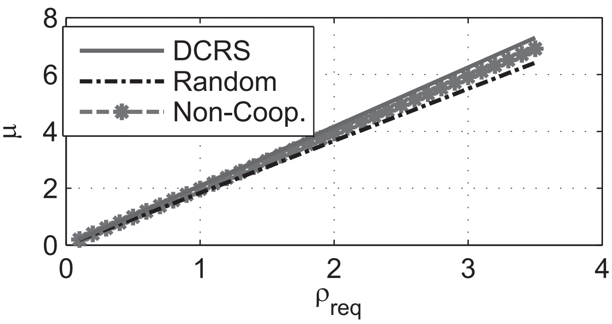


Fig. 5. Improvements in both spectral efficiency and energy efficiency for interference situations and different requirements.



(a)



(b)

Fig. 6. Improvements of both SE and EE w.r.t. interference situations and different requirements.

improved CDF performance of the proposed DCRS algorithm, we first show the improvements in both spectral efficiency and energy efficiency with more extensive settings, including the interference situations $5e-8 \sim 5e-7$ and different rate requirements, $\rho_{\rm req} = 0.1$ Mbps $\sim$ 3.5 Mbps, which are shown in Fig. 6.

We conclude that the energy efficiency decreases as the perceived interference increase (Fig. 6(a)), and spectral efficiency keeps increasing as the rate requirements increase (Fig. 6(b)). The results depend on the assumption of specific settings; for

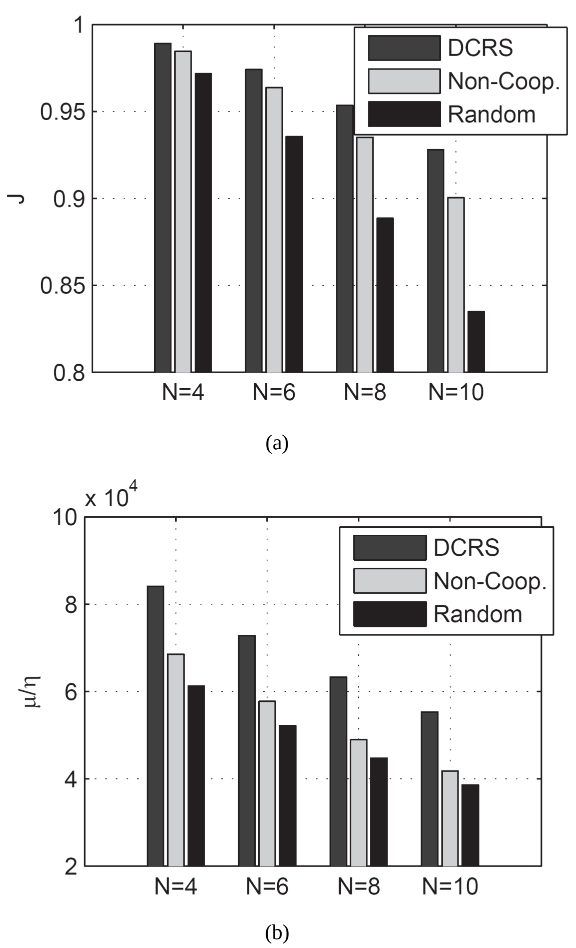


Fig. 7. Fairness and tradeoffs.

instance, there is no RAN that can individually serve these rate requirements, but any RAN reserves a certain capacity for potential concurrent traffic. However, the proposed DCRS scheme can always achieve the improved energy efficiency and spectral efficiency.

Only two players are considered in the above simulations. Here, we investigate multiple players: $N = 4, 6, 8, \text{and}\, 10$. When analyzing a Nash bargaining game, fairness is an important issue in the multiple player case. Here, in this paper, fairness means that $N-$players, refereed to as RANs will achieve a fair improved performance with respect to either energy efficiency or spectral efficiency. Here, we use Jain's fairness index as the criterion of fairness. This is mathematically computed as $J = \frac{\left(\sum_{i=1}^{N} \eta_i\right)^2}{N \sum_{i=1}^{N} \eta_i^2}$, where we use the achieved energy efficiency η as the measurement metric. Fig. 7 shows the fairness J and tradeoffs of μ/η, respectively. With an increasing number of players, both of fairness and the tradeoff decrease, and the proposed DCRS always attains some improved performance gain.

VII. CONCLUSION

Unlike most current studies that deal only with the spectral efficiency enhancement, we implement an optimal rate splitting strategy to improve both spectral efficiency and energy efficiency by exploring and exploiting cooperation diversity. First, we introduce the motivation for our proposed scheme and use the typical cooperative Nash bargaining game to formulate the problem. Then, we derive the best response function by analyzing the dual problem of the primal problem. The existence and uniqueness of the proposed Nash bargaining equilibrium are also proved, and more importantly, a distributed algorithm is designed to approach the optimal unique solution under mild conditions. Finally, we verify the convergence property, the effectiveness condition, and the improved performance of the proposed DCRS scheme. We evaluate the scheme with more extensive settings, including the interference situation, different requirements, and multiple players. In the future, we will concentrate on the analysis and implementation of the idea in the dynamic coalition case.

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