Hindawi
Journal of Computer Networks and Communications
Volume 2023, Article ID 5526441, 14 pages
https://doi.org/10.1155/2023/5526441

Research Article

Cooperative Game-Based Resource Allocation Scheme for Heterogeneous Networks with eICIC Technology

Sungwook Kim

Department of Computer Science, Sogang University, 35 Baekbeom-ro (Sinsu-dong), Mapo-gu, Seoul 04107, Republic of Korea

Correspondence should be addressed to Sungwook Kim; swkim01@sogang.ac.kr

Received 16 June 2023; Revised 25 July 2023; Accepted 17 August 2023; Published 28 August 2023

Academic Editor: Wanli Wen

Heterogeneous network (HetNet) is considered to be the most promising approach for increasing communication capacity. However, HetNet control problems are difficult due to their intertier interference. Recently, the enhanced intercell interference coordination (eICIC) technology is introduced to offer several benefits, including a more equitable traffic load distribution across the macro and embedded small cells. In this paper, we design a new resource allocation scheme for the eICIC-based HetNet. Our proposed scheme is formulated as a joint cooperative game to handle conflicting requirements. By adopting the ideas of Kalai and Smorodinsky solution (KSS), multicriteria Kalai and Smorodinsky solution (MCKSS), and sequential Raiffa solution (SRS), we develop a hybrid control algorithm for an adaptive resource sharing between different base stations. To effectively adjust the eICIC fraction rates, the concepts of MCKSS and SRS are applied in an interactive manner. For mobile devices in the HetNet, the assigned resource is distributed by using the idea of KSS. The key insight of our algorithm is to translate the originally competitive problem into a hierarchical cooperative problem to reach a socially optimal outcome. The main novelty of our approach is its flexibility to reach a reciprocal consensus under dynamic HetNet environments. Exhaustive system simulations illustrate the performance gains along different dimensions, such as system throughput, device payoff, and fairness among devices. The superiority of our proposed scheme is fully demonstrated in comparison with three other existing eICIC control protocols.

1. Introduction

As the commercial deployment of the fifth-generation (5G) of cellular networks is well underway in many countries of the world, academia as well as industrial research organizations turn their attention to how to improve the performance of the network system. With the exponential growth of mobile Internet of Things (IoT) devices, the 5G wireless communication system is designed to enhance the capacity 1000 times compared with the fourth-generation (4G) network system. The 5G network system integrates diverse communication technologies, such as mobile edge computing, cloud computing, cloud radio access networks, and device-to-device communications, to realize the IoT paradigm. However, the integration of different communication technologies brings some problems, such as limited wireless spectrum resources, high cost of underpinning infrastructure, and the difficulty of service quality maintenance. To solve these various control problems arising from the 5G network system, many researchers direct their notice to new innovative technologies [1].

From the aspect of network architecture, heterogeneous networks (HetNets) have attracted interests for their enhanced system performance. The deployment of low-power small base stations (SBSs) within a macrobase station (MBS) coverage area is a cost-effective solution to handle the extended traffic requests. To meet growing traffic loads, a large number of SBSs can be deployed in HetNet so that simultaneous transmissions of multiple IoT devices become possible. Compared with homogeneous networks (HomNets), HetNets can increase the opportunity in the spatial resource reuse by developing small cells into the coverage of macrocells. Specifically, HetNets allow different types of small cells to coexist with a macrocell by sharing the same spectrum resources. This approach can extremely improve the spectrum efficiency while reducing uncovered areas. Due to these merits, wireless networks have evolved from HomNets to HetNets [1, 2].

Motivated by the abovementioned advantages and characteristics of HetNets, many studies on HetNets have begun to be investigated. One of the main challenges in HetNets is the macrocell to small-cell interference. In HetNets, SBSs are characterized by low transmission power. Generally, most IoT devices refer to the maximal signal to interference and noise ratio (SINR) criterion to select their corresponding cells. Therefore, IoT devices may connect to a distant MBS due to its high transmission power rather than to any nearby SBS. It leads to an inefficient load distribution. Due to this reason, it is clear that the benefits of HetNets strongly depend on an efficient resource management between high-power MBS and low-power SBS [3–5].

For the resource management of HetNets, the 3rd Generation Partnership Project (3GPP) has proposed the notion of enhanced intercell interference coordination (eICIC). As a time-domain solution, the eICIC uses two mechanisms, i.e., Cell Range Extension (CRE) and Almost Blank Subframes (ABSs), to protect the small-cell transmissions by mitigating the interference from the MBS. The CRE is a technique to expand a small-cell range virtually by adding a bias value to the received power; it can be realized by performing user association. Therefore, small-cell coverage, cell-edge throughput, and overall network throughput can be improved. The ABS is a technique to mitigate the interference experienced by small-cell devices in cell range expansion region. During certain time intervals, the MBS is muted except for overhead signal transmissions to improve SINRs to the small-cell devices. These intervals are called ABS. Thus, multiple IoT devices can transmit to their corresponding SBSs over ABS with very little interference from the MBS [3–5].

To implement the eICIC technology, joint resource allocation among MBSs and SBSs is vitally important to reduce the mutual interference and achieve spectrum sharing. Since the proportion of ABSs is closely related to the association of device and the resource allocation scheme adopted by the SBSs, it is of critical importance that the proportion of ABSs, user association, and the resource allocation decisions should be jointly optimized so as to achieve the HetNet performance gain. In this paper, we aim to design a novel control scheme for the joint resource allocation problem involving the following three fundamental issues: (i) how to determine user association for load balancing, (ii) how to decide the optimal proportion of ABSs and which devices are allocated on ABSs or non-ABSs in time domain, and (iii) how to allocate spectrum resource in frequency domain. These three control issues are tightly coupled with each other. To optimize the system performance and realize the potential of HetNets, it is necessary to study these control problems jointly [6, 7].

Cooperative optimization is inspired by the principle of coordination work, which considers the interactions among agents to optimize their payoffs through their objective functions. It has a solid theoretical foundation and outstanding practical performance, which has aroused widespread attention and research interest. As a branch of cooperative optimization, cooperative game theory is concerned with the game players forming alliances and working together to achieve their common goals. In the cooperative games, how to decompose the reward generated by the grand alliance to each participant has always been a hot research topic. At present, cooperative game models are present in almost every field of research such as economics, biology, sociology, politics, computer science, and telecommunications. In this study, we adopt the basic idea of cooperative game theory to develop a novel resource control scheme for the eICIC-based HetNet platform. From the perspective of coordination, the MBS, SBSs, and IoT devices cooperate and diffuse information so as to obtain a globally optimal solution to maximize the HetNet system performance [8, 9].

The rest of this article is organized as follows. In Section 2, we describe the basic ideas of cooperative game solutions and main contributions of this study. Section 3 summarizes the state-of-the-art research papers related to the control issues for eICIC-based HetNets. Section 4 presents the scenario of HetNet system platform and formulates the control problem. And then, our proposed scheme is elaborated in detail by using different solution concepts. To help readers understand better, we also provide the primary steps of the proposed algorithm. Section 5 presents the testbed implementation setup and simulation results are shown along with the achieved experimental results. Finally, a conclusion is drawn and future research plans are explained in Section 6.

2. Technical Concepts and Main Contributions

In a cooperative game, multiple players have to agree on a feasible utility allocation. The key idea is that players can achieve superior outcomes by working together rather than working against each other. In 1950, it was originated in a fundamental paper by J. Nash. He introduced an idealized representation of the cooperative problem and developed a methodology that gave the hope that the uncertainty of cooperation could be resolved. Nash solution for cooperative games is that under certain axioms, there is a unique solution. However, one of his axioms, i.e., independence of irrelevant alternatives (IIAs), came under criticism. Since then, different solution concepts have been provided with alternative axiom; they also lead to another unique solutions. The most famous of them is the Kalai and Smorodinsky solution (KSS). It is suggested as an alternative to Nash's solution, which was suggested 25 years earlier. The main difference between the two solutions is that the Nash solution satisfies the IIA axiom, while the KSS solution satisfies the axiom of monotonicity [9, 10].

Recently, multicriteria cooperative games are concerned with situations in which a number of players must take into account several criteria, each of which depends on the decision of all players. A multicriteria cooperative game is a generalization of the classic cooperative game, where each player has a set of criteria for the evaluation of any decision. In these situations, there are two decision issues to be jointly considered: one related to the preferences of individual players with respect to their own criteria and the other related to the problem of selecting a solution that could be accepted by all the rational game players. However, until now, the literature on multicriteria cooperation is scarce. In 2009, the idea of multicriteria Kalai and Smorodinsky solution (MCKSS) was introduced while maintaining the multidimensional nature of each player's payoff. An important feature of MCKSS is that the set of feasible outcomes is a polyhedron, and as a consequence, if the solution can be rationalized by means of linear functions, then the outcomes induced by the solution can be computed by solving multicriteria linear problems [11].

As another cooperative game solution, H. Raiffa introduced the concept of sequential Raiffa solution (SRS) for a two-player cooperative problem. Based on the arbitration protocol, the *SRS* can be characterized by the standard cooperative game axioms. In addition, an additional specific axiom expresses the key concept of repeated negotiation of the same procedure to the decreasing sequence of remaining games. Given a disagreement point, the most preferred outcome for a player is the one that gives his maximal utility while keeping the other player at his disagreement payoff. The interim agreement is the average of these two, most preferred points. By using each interim agreement as a new disagreement point, the SRS sequentially repeats this cooperative game process and converges to a Pareto optimal point of the cooperative game set. By doing so, the *SRS* bridges the gap between cooperative and noncooperative game processes via relative gains and concessions [12, 13].

In this study, we aim to optimize the performance of eICIC-based HetNets. Based on the KSS, MCKSS, and SRS, our proposed scheme is designed as a joint control paradigm in a step-by-step repeated manner. During the interactions between the MBS and SBSs, the situation of multicriteria cooperation arises. Therefore, we formulate the MBS-SBSs control problem as a multicriteria cooperative game. In the viewpoint of each individual SBS, control issues can be modeled as a two-player cooperative game. For individual IoT devices, the assigned resource can be shared according to the single-criterion cooperative game. In the proposed scheme, these three cooperative game models are sophisticatedly combined in a dynamic interactive manner and work together during HetNet operations. In the eICIC-based HetNet system infrastructure, our joint control approach can harness the synergies of cooperation among MBS, SBSs, and IoT devices to achieve a socially optimal solution. The significant major contributions of our study are summarized as follows:

(1) To maximize the resource efficiency in the HetNet platform, we design a joint resource allocation scheme based on cooperative games. To the best of our knowledge, our cooperative game-based resource control paradigm is the first in the literature for the eICIC-based network infrastructure.

(2) To decide the fraction ratio for the MBS-SBSs control problem, we formulate a multicriteria cooperative game model and select best strategies based on the idea of MCKSS. To choose the fraction rate for each individual SBS service, we formulate a two-person cooperative game model and adopt the idea of SRS.

(3) For multiple IoT devices in the coverage areas of MBS or SBS, the resource distribution problem is solved based on the KSS. In a dynamically changing eICIC-based HetNet environment, three cooperative game processes are operated in a step-by-step repeated manner.

(4) Our cooperative game models are jointly combined and work together to get reciprocal advantages. With the eICIC technology, our hybrid approach explores the sequential interactions between MBS, SBSs, and IoT devices and reaches a consensus for the excellent HetNet performance.

(5) Extensive simulation results demonstrate the performance superiority of our proposed scheme by comparing to the existing state-of-the-art eICIC control protocols. Especially, the excellency of our cooperative game-based control paradigm is confirmed in terms of system throughput, device payoff, and fairness.

3. Related Work

After 3GPP has proposed the eICIC standard, academic research papers are largely focused on advancing the practical implication of eICIC-based HetNets. In this section, we touch on currently published papers relevant to the research topic of our study. In [14], Deb et al. proposed a novel radio resource sharing (RRS) scheme for eICIC in HetNets. Two important challenges in the RRS scheme are (i) to determine the amount of radio resources for the SBSs and (ii) to determine the device association rules for the SBSs. The RRS scheme addresses these two tightly coupled control issues in a joint manner. By using the notion of ABS and CRE, the RRS scheme can account for network topology, traffic load, and MBS-SBS interference map to guarantee the HetNet network performance. Therefore, the SBS transmissions are ensured without badly hit by interference from the MBS based on the enhanced intercell interference coordination implementation. Extensive simulations are conducted to study the performance evaluation, and numerical results show that RRS scheme can achieve better reliability and sustainability [14].

The paper [15] investigates the concept of dual-connectivity, joint device association, and resource allocation for HetNets. The benefits of dual-connectivity paradigm necessitate the careful device association and resource allocation techniques in the dense HetNet scenario. To control the problem of intertier interference, the dual-connectivity resource allocation (DRA) scheme is developed. First, in dual-connectivity enabled HetNets, the joint problem of device association and resource allocation is formulated as a mixed integer nonlinear programming problem. Second, by linearizing the products of the variables, the original problem is reformulated as a tractable linear problem, which is optimized to maximize the overall network throughput. Third, a new low-complexity heuristic method is designed to achieve the near-optimal system solution. Last, numerical results confirm that the DRA scheme outperforms in the average system throughput with less computation-time and low complexity [15].

The joint association and fairness (JAF) scheme is designed for the eICIC-based HetNet. [16]. This scheme concentrates on the joint device association and interference coordination problem, and it is formulated as a network--wide max-min fairness problem. However, it is a mixed integer nonlinear programming problem, which is NP-hard. To overcome this computation difficulty, this NP-hard problem is decomposed into two phase subproblems. The first subproblem is defined as the ABS ratio problem for given device association; it figured out the explicit expression of the optimal ABS ratio. Based on this derived result, the second subproblem is defined to maximize network utility through the device association. Based on the marginal utility, a new low complexity greedy algorithm with polynomial complexity is proposed to solve the second subproblem. Finally, simulation results show that the JAF scheme has good performance in terms of system throughput and fairness among mobile devices [16].

As discussed above, the earlier schemes in [14–16] have been studied on the resource allocation problem for the eICIC-based HetNet. Although these studies tackled the same control issues, which we concern in this study, they did not consider a joint control paradigm based on the cooperative game theory. Unlike the aforementioned RRS, DRA, and JAF schemes, our proposed scheme concerns the combination of different cooperative game solutions for controlling the activities of MBS, SBSs, and mobile IoT devices and guides them toward a fair-efficient outcome in the HetNet platform.

4. Proposed Resource Control Scheme for eICIC-Based HetNets

This section introduces the HetNet platform that we focus on. Then, we explain the basic ideas of KSS, MCKSS, and SRS, which are adopted to design our proposed joint control scheme. After that, our proposed resource allocation algorithm is described strategically in the nine-step procedures.

4.1. HetNet System Infrastructure and Cooperative Game Models. This paper focuses on an orthogonal frequency-division multiple-access HetNet consisting of MBSs overlaid with multiple open access low-power SBSs. Assume that in the two-tier HetNets, SBSs are randomly distributed within the coverage of each MBS, and the sets of MBSs and SBSs are denoted by $\mathbb{M} = \{\mathscr{M}_1, \ldots, \mathscr{M}_n\}$ and $\mathbb{S} = \{\mathscr{S}_1, \ldots, \mathscr{S}_m\}$, respectively. MBSs and SBSs are cochannel deployed and synchronous configured. The IoT devices $\mathbb{D} = \{\mathscr{D}_1, \ldots, \mathscr{D}_l\}$, which are connected to MBSs or SBSs, are assigned a number of subchannels. Assume the whole channel is flat fading and each base station allocates same power on every subchannel. Individual IoT devices are randomly placed in the cellular network area following a uniform distribution. Base stations carry out the spectrum resource management, scheduling, admit control, and more functionalities for their corresponding devices. As depicted in Figure 1, IoT devices can access different base stations, such as MBS or SBS, and we summarize the notations used in this paper in Table 1 [14–16].

To alleviate the traffic load of MBSs in HetNets, we employ time-domain eICIC mechanism. Assume a same ABS pattern that each MBS has the same ABS ratio α, where α fraction is assigned to ABS and $(1-\alpha)$ fraction is assigned to non-ABS. MBS maintains silence in the ABS position and transmits at normal power in a non-ABS position. Therefore, each MBS can only use the non-ABSs mode to serve its corresponding devices. However, SBSs can serve their corresponding devices by using the ABS or non-ABS mode. In the HetNet platform, we define the IoT devices within the nominal coverage of the SBS as SBS-centric devices. By assigning a positive bias to the reference signal received power, the SBS coverage area can be extended. The devices in the SBS-extended range are defined as SBS-extended devices. Over the non-ABS mode, the SBS-extended devices suffer excessive interference from MBS, while the SBS-centric devices receive relatively less interference [7, 14–16].

Without loss of generality, it is assumed that the SBS-centric and SBS-extended devices are served by non-ABS and ABS, respectively. However, some SBS-centric devices are seriously interfered by MBS. In order to solve this problem, we configure a certain proportion of ABS fraction by using ratio factor β. Therefore, the resource scheduling policy of SBS is to serve the SBS-extended devices by using the β proportion of ABS fraction, while $(1-\beta)$ proportion of ABS fraction is assigned for the SBS-centric devices. Based on the eICIC technology, the values of α and β are dynamically adjusted to share the limited spectrum resource to maximize the HetNet system. By combining the time domain and the frequency domain, the diagram of spectrum allocation for the MBS and SBS is shown in Figure 2.

During the eICIC operations, each SBS has two type devices. Devices are served on ABS mode (the set denoted by $\mathbb{D}_{\mathscr{S}}^{A}$), and the other devices are served on non-ABS mode (the set denoted by $\mathbb{D}_{\mathscr{S}}^{nA}$). Each MBS only uses the non-ABS mode to serve their corresponding devices, which are denoted by the set $\mathbb{D}_{\mathscr{M}}$. Therefore, we have $|\mathbb{M}| + 2 \times |\mathbb{S}|$ virtual base stations in total. The SINR of $\mathscr{D}_j \in \mathbb{D}$ from virtual base station $\mathscr{V}$ is given by the following equation [16]:

$$\mathrm{SINR}_{\mathscr{D}_j,\mathscr{V}} = \frac{P_{\mathscr{V}} \times \left|h_{\mathscr{D}_j,\mathscr{V}}\right|^2}{\sum_{\mathscr{Q}\in\mathscr{T}_{\mathscr{D}_j}}\left(P_{\mathscr{Q}} \times \left|h_{\mathscr{D}_j,\mathscr{Q}}\right|^2\right) + \sigma^2}, \quad (1)$$

where $P_{\mathscr{V}}$ is the transmission power of $\mathscr{V}$, $|h_{\mathscr{D}_j,\mathscr{V}}|^2$ is the channel gain from $\mathscr{V}$ to $\mathscr{D}_j$, and σ^2 is the noise power of each base station. $\mathscr{T}_{\mathscr{D}_j}$ denotes the interfering device set of $\mathscr{D}_j$. When $\mathscr{D}_j$ is served on ABS mode, $\mathscr{T}_{\mathscr{D}_j} = \mathbb{D}_{\mathscr{S}}^{A}/\{\mathscr{V}\}$; otherwise, $\mathscr{T}_{\mathscr{D}_j} = \mathbb{M} \cup (\mathbb{D}_{\mathscr{S}}^{nA}/\{\mathscr{V}\})$. Based on the quasistatic fading channel, $\mathrm{SINR}_{\mathscr{D}_j,\mathscr{V}}$ is assumed to be constant during an allocation period. According to the Shannon capacity, the instantaneous communication rate from $\mathscr{V}$ to $\mathscr{D}_j$, i.e., $r_{\mathscr{D}_j,\mathscr{V}}$, can be obtained, and we finally get the normalized link rate from $\mathscr{V}$ to $\mathscr{D}_j$, i.e., $R_{\mathscr{D}_j,\mathscr{V}}$ as follows [3, 16]:

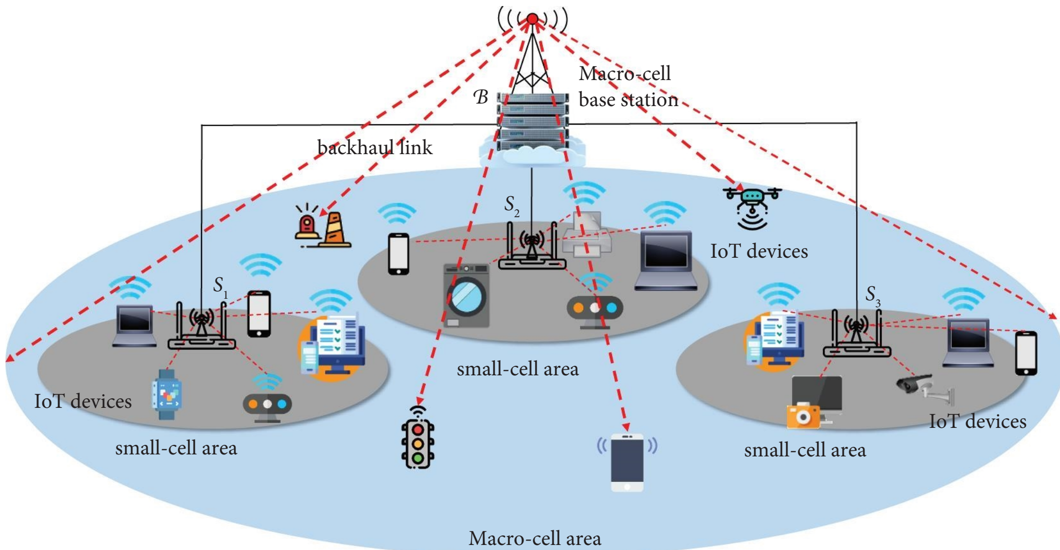

Figure 1: A general two-tier heterogeneous network infrastructure.

$$R_{\mathscr{D}_j,\mathscr{V}} = \begin{cases} (1-\alpha) \times r_{\mathscr{D}_j,\mathscr{V}}, & \text{if } \mathscr{V} \in \mathbb{M}, \\ \alpha \times \beta \times r_{\mathscr{D}_j,\mathscr{V}}, & \text{if } \mathscr{V} \in \mathbb{D}_{\mathscr{S}}^{A}, \\ (1-(\alpha \times \beta)) \times r_{\mathscr{D}_j,\mathscr{V}}, & \text{if } \mathscr{V} \in \mathbb{D}_{\mathscr{S}}^{nA}, \end{cases} \tag{2}$$
$$\text{s.t.,} \quad r_{\mathscr{D}_j,\mathscr{V}} = W \times \log\left(1 + \text{SINR}_{\mathscr{D}_j,\mathscr{V}}\right),$$

where W is the channel bandwidth from $\mathscr{V}$ to $\mathscr{D}_j$. In this paper, we develop three cooperative games, which are hierarchically organized based on the joint control paradigm. The first cooperative game $(\mathbb{G}_{\mathscr{S}}^{\mathscr{M}})$ decides the ABS ratio α, and the second cooperative game $(\mathbb{G}_{\mathscr{S}})$ decides the proportion ratio factor β for each SBS. Finally, the third cooperative game $(\mathbb{G}_{\mathscr{D}})$ distributes the assigned resource for corresponding IoT devices. Through the $\mathbb{G}_{\mathscr{S}}^{\mathscr{M}}$, $\mathbb{G}_{\mathscr{S}}$, and $\mathbb{G}_{\mathscr{D}}$ games, the MBS, SBSs, and devices are sequentially interacted with each other to reach a mutually acceptable solution, which is called social optimal consensus. It is noteworthy that we formulate the $\mathscr{M}$-$\mathscr{S}$-$\mathscr{D}$ association in an iterative coordinated manner. Formally, we define the tuple entities in our proposed $\mathbb{G}_{\mathscr{S}}^{\mathscr{M}}$, $\mathbb{G}_{\mathscr{S}}$, and $\mathbb{G}_{\mathscr{D}}$ game models, such as

$$\begin{aligned} \mathbb{G} &= \left\{\mathbb{G}_{\mathscr{S}}^{\mathscr{M}}, \mathbb{G}_{\mathscr{S}}, \mathbb{G}_{\mathscr{D}}\right\} = \left\{\mathbb{M}, \mathbb{S}, \mathbb{D}, \mathbb{G}_{\mathscr{S}}^{\mathscr{M}_i} = \left\{\left(\mathscr{M}_i, \mathbb{S}_{\mathscr{M}_i}\right), \mathfrak{M}_{\mathscr{M}_i}, \alpha_{\mathscr{M}_i}, \left(U_{\mathscr{M}_i}(\cdot), U_{\mathbb{S}_{\mathscr{M}_i}}(\cdot)\right)\right\}, \right. \\ \mathbb{G}_{\mathscr{S}_j} &= \left\{\left(\mathbb{D}_e^{\mathscr{S}_j}, \mathbb{D}_c^{\mathscr{S}_j}\right), \beta_{\mathscr{S}_j}, \left(\mathscr{U}_e^{\mathscr{S}_j}(\cdot), \mathscr{U}_c^{\mathscr{S}_j}(\cdot)\right)\right\}, \mathbb{G}_{\mathscr{D}} = \left\{\mathbb{G}_{\mathscr{D}}^{\mathscr{M}_i}, \mathbb{G}_e^{\mathscr{S}_j}, \mathbb{G}_c^{\mathscr{S}_j} \middle| \mathbb{D}_{\mathscr{M}_i}, \mathbb{D}_e^{\mathscr{S}_j}, \mathbb{D}_c^{\mathscr{S}_j}, \mathscr{D}_k, \mathfrak{R}_{\mathscr{D}_k}, \mathfrak{U}_{\mathscr{D}_k}(\cdot)\right\}, \left. T\right\}. \end{aligned} \tag{3}$$

(1) $\mathbb{M}$, $\mathbb{S}$, and $\mathbb{D}$ represent the sets of MBSs, SBSs, and IoT devices, respectively

(2) In the first game for $\mathscr{M}_i$, i.e., $\mathbb{G}_{\mathscr{S}}^{\mathscr{M}_i}$, $\mathbb{S}_{\mathscr{M}_i}$ represents the set of SBSs, which exist in $\mathscr{M}_i$'s coverage area, and we assume that $\mathbb{S}_{\mathscr{M}_i}$ is an individual game player. $\mathfrak{M}_{\mathscr{M}_i}$ is $\mathscr{M}_i$'s spectrum resource amount.

(3) In $\mathbb{G}_{\mathscr{S}}^{\mathscr{M}_i}$, $\mathscr{M}_i$ and $\mathbb{S}_{\mathscr{M}_i}$ are the game players, and $(1-\alpha_{\mathscr{M}_i})$, $\alpha_{\mathscr{M}_i}$ are their strategies, and $U_{\mathscr{M}_i}(\cdot)$ and $U_{\mathbb{S}_{\mathscr{M}_i}}(\cdot)$ are their utility functions, respectively.

(4) In the second game for $\mathscr{S}_j$, i.e., $\mathbb{G}_{\mathscr{S}_j}$, $\mathbb{D}_e^{\mathscr{S}_j}$ is the set of $\mathscr{S}_j$-extended devices, and $\mathbb{D}_c^{\mathscr{S}_j}$ is the set of $\mathscr{S}_j$-centric devices. We also assume that $\mathbb{D}_e^{\mathscr{S}_j}$ and $\mathbb{D}_c^{\mathscr{S}_j}$ are individual game players.

(5) In $\mathbb{G}_{\mathscr{S}_j}$, $\mathbb{D}_e^{\mathscr{S}_j}$, $\mathbb{D}_c^{\mathscr{S}_j}$ are the game players, and $\beta_{\mathscr{S}_j}$, $(1-\beta_{\mathscr{S}_j})$ are their strategies, and $\mathscr{U}_e^{\mathscr{S}_j}(\cdot)$, $\mathscr{U}_c^{\mathscr{S}_j}(\cdot)$ are their utility functions, respectively.

(6) In the third game for IoT devices, i.e., $\mathbb{G}_{\mathscr{D}}$, there are three subgames such as $\mathbb{G}_{\mathscr{D}}^{\mathscr{M}_i}$, $\mathbb{G}_e^{\mathscr{S}_j}$, and $\mathbb{G}_c^{\mathscr{S}_j}$. When $\mathscr{S}_j$ is included in $\mathscr{M}_i$'s covering area, $\mathbb{D}_{\mathscr{M}_i}$ is the set of $\mathscr{M}_i$'s corresponding devices, $\mathbb{D}_e^{\mathscr{S}_j}$ is the set of $\mathscr{S}_j$-extended devices, and $\mathbb{D}_c^{\mathscr{S}_j}$ is the set of $\mathscr{S}_j$-centric devices.

(7) In $\mathbb{G}_{\mathscr{D}}^{\mathscr{M}_i}$, $\mathbb{G}_e^{\mathscr{S}_j}$, and $\mathbb{G}_c^{\mathscr{S}_j}$, devices in $\mathbb{D}_{\mathscr{M}_i}$, $\mathbb{D}_e^{\mathscr{S}_j}$, and $\mathbb{D}_c^{\mathscr{S}_j}$ are game players, respectively. For $\mathscr{D}_k \in \left\{\mathbb{D}_{\mathscr{M}_i} \cup \mathbb{D}_e^{\mathscr{S}_j} \cup \mathbb{D}_c^{\mathscr{S}_j}\right\}$, $\mathfrak{R}_{\mathscr{D}_k}$ and $\mathfrak{U}_{\mathscr{D}_k}(\cdot)$ are $\mathscr{D}_k$'s strategy and utility function, respectively.

Table 1: The notations for abbreviations, symbols, and parameters.

Acronyms	Explanations
HetNet	Heterogeneous network
eICIC	Enhanced inter-cell interference coordination
KSS	Kalai and Smorodinsky solution
MCKSS	Multicriteria Kalai and Smorodinsky solution
SRS	Sequential Raiffa solution
IoT	Internet of Things
SBS	Small base station
MBS	Macro base station
HomNets	Homogeneous networks
SINR	Signal to interference and noise ratio
CRE	Cell range extension
ABS	Almost blank subframes
IIA	Independence of irrelevant alternatives
RRS	Radio resource sharing
DRA	Dual-connectivity resource allocation
JAF	Joint association and fairness
Notations	**Explanations**
$\mathbb{M} = \{\mathcal{M}_1, \ldots, \mathcal{M}_n\}$	The sets of MBSs
$\mathbb{S} = \{\mathcal{S}_1, \ldots, \mathcal{S}_m\}$	The sets of SBSs
$\mathbb{D} = \{\mathcal{D}_1, \ldots, \mathcal{D}_l\}$	The sets of IoT devices
α	A fraction ratio for ABS
β	A ABS fraction ratio for SBS-extended devices
$\mathbb{D}^{A}_{\mathcal{S}}$	Devices are served on ABS mode
$\mathbb{D}^{nA}_{\mathcal{S}}$	Devices are served on non-ABS mode
$P_{\mathcal{V}}$	The transmission power of $\mathcal{V}$
$\mathcal{T}_{\mathcal{D}}$	The interfering device set of $\mathcal{D}$
W	The channel bandwidth
$\mathbb{G}^{\mathcal{M}}_{\mathcal{S}}$	The cooperative game to decide the ABS ratio α
$\mathbb{G}_{\mathcal{S}}$	The cooperative game to decide the ratio factor β
$\mathbb{G}_{\mathcal{D}}$	The cooperative game to distribute the assigned resource for IoT devices
$\mathbb{S}_{\mathcal{M}}$	The set of SBSs, which exist in the $\mathcal{M}$'s coverage area
$\mathfrak{M}_{\mathcal{M}}$	The $\mathcal{M}$'s spectrum resource amount
$U_{\mathcal{M}}(\cdot)$	The $\mathcal{M}$'s utility function
$U_{\mathbb{S}_{\mathcal{M}}}(\cdot)$	The $\mathbb{S}_{\mathcal{M}}$'s utility function
$\mathbb{D}_e^{\mathcal{S}^{\mathcal{M}}}$	The set of $\mathcal{S}$-extended devices
$\mathbb{D}_c^{\mathcal{S}}$	The set of $\mathcal{S}$-centric devices
$\mathcal{U}_e^{\mathcal{S}}(\cdot)$	The $\mathbb{D}_e^{\mathcal{S}}$'s utility function
$\mathcal{U}_c^{\mathcal{S}}(\cdot)$	The $\mathbb{D}_c^{\mathcal{S}}$'s utility function
$\mathfrak{R}_{\mathcal{D}}$	The $\mathcal{D}$'s strategy
$\mathfrak{U}_{\mathcal{D}}(\cdot)$	The $\mathcal{D}$'s utility function
η, δ	Control parameters for $U^S_{\mathcal{M}}(\cdot)$
ζ	A control parameter for $U^P_{\mathcal{M}}(\cdot)$
μ	A control parameters for $U^S_{\mathbb{S}_{\mathcal{M}}}(\cdot)$
ϱ, ω, ψ	Control parameters for $U^P_{\mathbb{S}_{\mathcal{M}}}(\cdot)$
$\mathcal{I}^S_i$	The ideal outcome of sensitivity
$\mathcal{I}^P_i$	The ideal outcome of productivity
d^S_i	The disagreement point of sensitivity
d^P_i	The disagreement point of productivity
κ	A control parameter for $\mathcal{U}_e^{\mathcal{S}}(\cdot)$
ε, ξ	Control parameters for $\mathcal{U}_c^{\mathcal{S}}(\cdot)$
$\mathfrak{R}^e_{\mathbb{S}_{\mathcal{M}}}$	The total requested resource amounts from $\mathbb{D}_e^{\mathcal{S}}$
$\mathfrak{R}^c_{\mathbb{S}_{\mathcal{M}}}$	The total requested resource amounts from $\mathbb{D}_c^{\mathcal{S}}$
d_e	The disagreement points for $\mathbb{D}_e^{\mathcal{S}}$
d_c	The disagreement points for $\mathbb{D}_c^{\mathcal{S}}$
φ	A predefined minimum bound
$\mathfrak{R}_{\mathcal{D}}$	The requested resource amount for $\mathcal{D}$
$\Gamma_{\mathcal{D}}$	The allocated resource amount for $\mathcal{D}$
$\mathcal{I}_{\mathcal{D}}$	The ideal outcome for $\mathcal{D}$

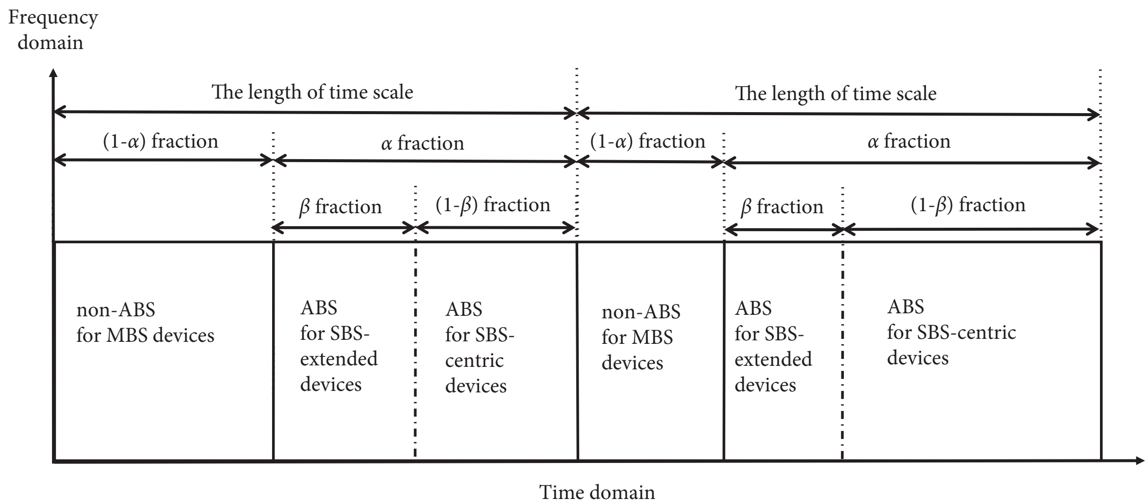

Figure 2: Principle of allocation of spectrum resource in the eICIC technique.

(8) Discrete time model $T \in \{t_1, \ldots, t_c, t_{c+1}, \ldots\}$ is represented by a sequence of time steps. The length of t_c matches the event time-scale of $\mathbb{G}_{\mathcal{S}}^{\mathcal{M}}$, $\mathbb{G}_{\mathcal{S}}$, and $\mathbb{G}_{\mathcal{D}}$.

4.2. Technical Concepts and Ideas of KSS, MCKSS, and SRS. In this subsection, we quickly review the fundamental concepts of KSS, MCKSS, and the sequential Raiffa solution for cooperative games.

4.2.1. Multicriteria Kalai and Smorodinsky Solution for Cooperative Games. To characterize the basic concept of MCKSS, we preliminarily define some mathematical expressions. Let $\mathbb{N} = \{1, 2, \ldots, n\}$ be the set of players, and each player considers the same m criteria, $\mathcal{M} = \{1, 2, \ldots, m\}$, to value the possible agreements. An n-person multicriteria cooperative game is formally described by the pair (S, d), where $S \subseteq \mathbb{R}^{n\times m}$ is the set of all feasible outcomes and $d = \times_{i=1}^{n} d_i$ is the disagreement point or status quo. The outcomes in S are obtained as the result of a joint decision of all the players. Therefore, there exists an agreement $X = (x_1, x_2, \ldots, x_n) \in S$ that gives the player $i \in \mathbb{N}$ an outcome vector $x_i = (x_i^1, x_i^2, \ldots, x_i^m) \in \mathbb{R}^m$, where $x_i^{1\le j\le m}$ is the payoff of player i in criterion j. d is the result obtainable if the players fail to reach an agreement. In a multicriteria cooperative game, individual rationality establishes that each player will only negotiate at or above those outcomes that improve upon the disagreement point d. Thus, the set of outcomes where players will negotiate is $d^{\geq} = \{X \in \mathbb{R}^{n\times m} | X \geq d^{\geq}\}$ [11].

Usually, a multicriteria cooperative game solution is a procedure to incorporate partial information on the importance of the criteria in multicriteria linear problems. Based on this idea, MCKSS takes into account each player's maximum payoffs with respect to the criteria, which are represented by the ideal outcomes; they are denoted as $\mathcal{I} = (\mathcal{I}_{i\in\mathbb{N}}^{1\le j\le m})$. MCKSS is obtained by replacing the payoff gains of players by the proportion with respect to their ideal outcomes. Therefore, for each feasible outcome $X = (x_1, x_2, \ldots, x_n) \in S$, the quotient $(x_i^j - d_i^j)/(\mathcal{I}_i^j - d_i^j)$ is a major decision factor, where $i \in \mathbb{N}$ and $1 \le j \le m$. Originally, E. Kalai and M. Smorodinsky introduced the idea of KSS as a single criterion cooperative game solution. It provides a payoff that is proportional to the achievable maximum payoff while ensuring efficiency. Therefore, each player gets the same fraction of his maximum possible payoff in KSS. Geometrically, KSS is the intersection point between the cooperative game set S and the straight line between the disagreement point and the utopian point. By considering single criterion X and $\mathcal{I}$, the KSS, i.e., $X^{\mathrm{KSS}} = (x_1^*, x_2^*, \ldots, x_n^*)$, must satisfy the following equation [10, 11]:

$$X^{\mathrm{KSS}} = \max_X \left\{ X \middle| \frac{x_1^* - d_1}{\mathcal{I}_1 - d_1} = \frac{x_2^* - d_2}{\mathcal{I}_2 - d_2} = \cdots = \frac{x_n^* - d_n}{\mathcal{I}_n - d_n} \right\},$$
$$\text{s.t., } X^{\mathrm{KSS}} = (x_1^*, x_2^*, \ldots, x_n^*) \in S. \tag{4}$$

To define MCKSS, let $\mathfrak{P}(X)$ denote the minimum proportional payoff vector whose components are $\mathfrak{P}^j(X) = \min_{1\le i\le n}\left\{1 \le j \le m | (x_i^j - d_i^j)/(\mathcal{I}_i^j - d_i^j)\right\}$. For each feasible outcome $X \in S$, the minimum utility gains vector is $\varkappa(X) = (\varkappa^1(X), \varkappa^2(X), \ldots, \varkappa^m(X))$, where $\varkappa^{1\le j\le m}(X) = \min_{1\le i\le n}\left\{x_i^j - d_i^j\right\}$. Each component of $\varkappa(X)$ represents the guaranteed minimum utility gains of the set of players for the corresponding criterion. MCKSS is based on the idea that the players jointly agree on those outcomes whose minimum utility gain levels cannot be simultaneously improved with respect to all the criteria. Therefore, the players will choose an outcome such that there is no other outcome whose minimum utility gain vector is better in terms of components. For the multicriteria cooperative game (S, d), a feasible outcome $X \in S \cap d^{\geq}$ is MCKSS, if there does not exist $Y \in S \cap d^{\geq}$ such that $\mathfrak{P}(Y) \geq \mathfrak{P}(X)$. Mathematically, MCKSS, i.e., $X^{\mathrm{MCKSS}} = (\widehat{x}_1, \widehat{x}_2, \ldots, \widehat{x}_n)$, is given by the following equation [11]:

$$X^{\mathrm{MCKSS}} = \left(\widehat{x}_1, \widehat{x}_2, \ldots, \widehat{x}_n\right) = \max \varkappa^1, \varkappa^2, \ldots, \varkappa^m,$$

$$\text{s.t.,} \begin{cases} \dfrac{x_i^1 - d_i^1}{\mathcal{I}_i^1 - d_i^1} \geq \varkappa^1, \quad \forall i = 1, 2, \ldots, n, \\ \vdots, \\ \vdots, \\ \dfrac{x_i^m - d_i^m}{\mathcal{I}_i^m - d_i^m} \geq \varkappa^m, \quad \forall i = 1, 2, \ldots, n, \\ X \in S \cap d^{\geq} \text{ and } \widehat{x}_{1 \leq i \leq n} = \left(x_i^1, x_i^2, \ldots, x_i^m\right). \end{cases} \tag{5}$$

Therefore, MCKSS is the Pareto optimal by criteria in $S \cap d^{\geq}$ and the set of efficient solutions for multicriteria cooperative game (S, d).

4.2.2. Sequential Raiffa Solution for Cooperative Game. To characterize the fundamental idea of *SRS*, we assume a two-player cooperative game problem. $\mathbb{R}$ is a real number set, and $\mathbb{R}^2$ denotes the two-dimensional Euclidean space. Let $S \subset \mathbb{R}^2$ be a nonempty and finite set, and $\mathbb{N}$ is a set of natural numbers. For any $x, y \in \mathbb{R}^2$, we write $x \geq y$ ($x \gg y$, resp.) if for any $i \in S$, $x_i \geq y_i$ ($x_i > y_i$, resp.). A pair (S, d) is a cooperative game with $d \in S \subset \mathbb{R}^2$, where $d \leq y \leq x \in S \Rightarrow y \in S$. The set of all two-person cooperative games is denoted as $\mathbb{B}$. For any nonempty subset C of $\mathbb{B}$, a mapping $F\colon C \longrightarrow \mathbb{R}^2\colon (S, d) \longmapsto F(S, d) \in S$ is called a cooperative solution on C. With $x \in \mathbb{R}^2$, let $\mathbf{1}_S$ be the indicator function of S, where $\mathbf{1}_S\colon \mathbb{R}^2 \longrightarrow \mathbb{R}\colon x \mapsto (1, \text{if } x \in S | 0, \text{if } x \notin S)$. For any game $(S, d) \in \mathbb{B}$, we consider the mapping $f^{(S,d)}\colon \mathbb{R}^2 \longrightarrow \mathbb{R}^2$; it defined as follows [13]:

$$f^{(S,d)}\left(x_1, x_2\right) := \left(f_1^{(S,d)}\left(x_2\right), f_2^{(S,d)}\left(x_1\right)\right),$$
$$\text{s.t.,} \begin{cases} f_1^{(S,d)}\colon \mathbb{R} \longrightarrow \mathbb{R}\colon x_2 \longmapsto f_1^{(S,d)}\left(x_2\right) := \mathbf{max}_{x_1 \in \mathbb{R}} \left(x_1 - d_1\right) \bullet l_s\left(x_1, x_2\right), \\ f_2^{(S,d)}\colon \mathbb{R} \longrightarrow \mathbb{R}\colon x_1 \longmapsto f_2^{(S,d)}\left(x_1\right) := \mathbf{max}_{x_2 \in \mathbb{R}} \left(x_2 - d_2\right) \bullet l_s\left(x_1, x_2\right). \end{cases} \tag{6}$$

Now consider the sequence $(m_k^{(S,d)})_{k \in \mathcal{N} = \{1,2,3,\ldots\}}$ defined by the following equation [13]:

$$m_{k \in \mathcal{N}}^{(S,d)} = \frac{1}{2} \times \left[\left(f_1^{(S,d)}\left(m_{k-1,2}^{(S,d)}\right), m_{k-1,2}^{(S,d)}\right) + \left(m_{k-1,1}^{(S,d)}, f_2^{(S,d)}\left(m_{k-1,1}^{(S,d)}\right)\right)\right],$$
$$\text{s.t.,}\, m_0^{(S,d)} := \left(m_{0,1}^{(S,d)}, m_{0,2}^{(S,d)}\right) := \left(d_1, d_2\right) = d. \tag{7}$$

According to (6) and (7), $SRS(S, d)$ is defined by the following equation [13]:

$$\mathrm{SRS}(S, d) := \lim_{k \in (\mathcal{N} \cup \{0\})} m_k^{(S,d)}, \text{s.t.}, \forall (S, d) \in \mathbb{B}. \tag{8}$$

4.3. The Proposed Joint Cooperative Game Model for the eICIC-Based HetNets. To develop our joint control scheme for the eICIC-based HetNet platform, we construct the $\mathbb{G}_{\mathcal{S}}^{\mathcal{M}}$, $\mathbb{G}_{\mathcal{S}}$, and $\mathbb{G}_{\mathcal{D}}$ game models. For n MBSs in $\mathbb{M}$, total $n\mathbb{G}_{\mathcal{S}}^{\mathcal{M}}$ game models are operated in a parallel manner. $\mathbb{G}_{\mathcal{S}}^{\mathcal{M}_i}$ is designed to decide the ABS ratio for $\mathcal{M}_i$ and $\mathbb{S}_{\mathcal{M}_i}$. In the $\mathbb{G}_{\mathcal{S}}^{\mathcal{M}_i}$ game, we concern two decision criteria such as real-time sensitivity and service productivity for communication services. Therefore, we adopt the idea of MCKSS for $\mathbb{G}_{\mathcal{S}}^{\mathcal{M}_i}$'s solution concept. In the $\mathbb{G}_{\mathcal{S}}^{\mathcal{M}_i}$ game, $\mathcal{M}_i$ and $\mathbb{S}_{\mathcal{M}_i}$ are the game players. For the game player $\mathcal{M}_i$, we define his utility function $U_{\mathcal{M}_i}(\cdot)$. However, $U_{\mathcal{M}_i}(\cdot)$ consists of two subfunctions for the criteria of sensitivity $(U_{\mathcal{M}_i}^S(\cdot))$ and productivity $(U_{\mathcal{M}_i}^P(\cdot))$, where $U_{\mathcal{M}_i}(\cdot) = \left\{U_{\mathcal{M}_i}^S(\cdot), U_{\mathcal{M}_i}^P(\cdot)\right\}$. They are given as follows:

$$U_{\mathcal{M}_i}\left(\left(\alpha^S_{\mathcal{M}_i}, \alpha^P_{\mathcal{M}_i}\right), \mathfrak{M}_{\mathcal{M}_i}, \mathfrak{R}_{\mathcal{M}_i}\right) = \begin{cases} U^S_{\mathcal{M}_i}(\cdot) = \eta \times \left(\exp\left(\delta \times \dfrac{\min\left(\mathfrak{R}_{\mathcal{M}_i}, \left(\left(1-\alpha^S_{\mathcal{M}_i}\right) \times \mathfrak{M}_{\mathcal{M}_i}\right)\right)}{\mathfrak{R}_{\mathcal{M}_i}} \right) - 1 \right), \\ U^P_{\mathcal{M}_i}(\cdot) = \log\left(\zeta \times \dfrac{\min\left(\mathfrak{R}_{\mathcal{M}_i}, \left(\left(1-\alpha^P_{\mathcal{M}_i}\right) \times \mathfrak{M}_{\mathcal{M}_i}\right)\right)}{\mathfrak{R}_{\mathcal{M}_i}} + 1 \right), \end{cases} \tag{9}$$

where η and δ are the control parameters for $U^S_{\mathcal{M}_i}(\cdot)$. $\mathfrak{R}_{\mathcal{M}_i}$ is the total resource request sum from the set $(\mathbb{D}_{\mathcal{M}_i})$ of $\mathcal{M}_i$'s corresponding devices, and $\mathfrak{M}_{\mathcal{M}_i}$ is $\mathcal{M}_i$'s spectrum resource amount. ζ is a control parameter for $U^P_{\mathcal{M}_i}(\cdot)$. For the another game player $\mathbb{S}_{\mathcal{M}_i}$, we define his utility function $U_{\mathbb{S}_{\mathcal{M}_i}}(\cdot)$ as the same manner as $U_{\mathcal{M}_i}(\cdot)$, where $U_{\mathbb{S}_{\mathcal{M}_i}}(\cdot) = \left\{U^S_{\mathbb{S}_{\mathcal{M}_i}}(\cdot), U^P_{\mathbb{S}_{\mathcal{M}_i}}(\cdot)\right\}$. They are given as follows:

$$U_{\mathbb{S}_{\mathcal{M}_i}}\left(\left(\alpha^S_{\mathcal{M}_i}, \alpha^P_{\mathcal{M}_i}\right), \mathfrak{M}_{\mathcal{M}_i}, \mathfrak{R}_{\mathcal{M}_i}\right) = \begin{cases} U^S_{\mathbb{S}_{\mathcal{M}_i}}(\cdot) = -\log\left(1 - \mu \times \dfrac{\min\left(\mathfrak{R}_{\mathbb{S}_{\mathcal{M}_i}}, \left(\alpha^S_{\mathcal{M}_i} \times \mathfrak{M}_{\mathcal{M}_i}\right)\right)}{\mathfrak{R}_{\mathbb{S}_{\mathcal{M}_i}}} \right), \\ U^P_{\mathbb{S}_{\mathcal{M}_i}}(\cdot) = \varrho \times \left(\dfrac{1}{1 + \exp\left(-\omega \times \min\left(\mathfrak{R}_{\mathbb{S}_{\mathcal{M}_i}}, \left(\alpha^P_{\mathcal{M}_i} \times \mathfrak{M}_{\mathcal{M}_i}\right)\right)/\mathfrak{R}_{\mathbb{S}_{\mathcal{M}_i}}\right)} - \psi \right), \end{cases} \tag{10}$$

where μ is a control parameter for $U^S_{\mathbb{S}_{\mathcal{M}_i}}(\cdot)$. $\mathfrak{R}_{\mathbb{S}_{\mathcal{M}_i}}$ is the total resource request sum from the corresponding devices in $\mathbb{S}_{\mathcal{M}_i}$. ϱ, ω, and ψ are the control parameters for $U^P_{\mathbb{S}_{\mathcal{M}_i}}(\cdot)$. For the multicriteria $\mathbb{G}^{\mathcal{M}_i}_{\mathcal{S}}$ game, MCKSS, i.e., $X^{\text{MCKSS}}(\mathbb{G}^{\mathcal{M}_i}_{\mathcal{S}})$, is obtained as follows:

$$\begin{aligned} X^{\text{MCKSS}}\left(\mathbb{G}^{\mathcal{M}_i}_{\mathcal{S}}\right) &= \left(\widehat{U}_{\mathcal{M}_i}(\cdot), \widehat{U}_{\mathbb{S}_{\mathcal{M}_i}}(\cdot)\right) \\ &= \mathbf{max}\, \varkappa^S, \varkappa^P, \\ &\text{s.t.,} \begin{cases} \dfrac{U^S_i(\cdot) - d^S_i}{\mathcal{I}^S_i - d^S_i} \geq \varkappa^S, \quad i = \left\{\mathcal{M}_i, \mathbb{S}_{\mathcal{M}_i}\right\}, \\ \dfrac{U^P_i(\cdot) - d^P_i}{\mathcal{I}^P_i - d^P_i} \geq \varkappa^P, \quad i = \left\{\mathcal{M}_i, \mathbb{S}_{\mathcal{M}_i}\right\}, \\ \widehat{U}_{\mathcal{M}_i}(\cdot) = \left(U^{S*}_{\mathcal{M}_i}(\cdot), U^{P*}_{\mathcal{M}_i}(\cdot)\right) \text{ and } \widehat{U}_{\mathbb{S}_{\mathcal{M}_i}}(\cdot) = \left(U^{S*}_{\mathbb{S}_{\mathcal{M}_i}}(\cdot), U^{P*}_{\mathbb{S}_{\mathcal{M}_i}}(\cdot)\right), \end{cases} \end{aligned} \tag{11}$$

where $\mathcal{I}^S_i$ and $\mathcal{I}^P_i$ are the ideal outcomes, and d^S_i and d^P_i are the disagreement points of sensitivity and productivity criteria, respectively. $\widehat{U}^S_{\mathcal{M}_i}(\cdot)$, $\widehat{U}^S_{\mathbb{S}_{\mathcal{M}_i}}(\cdot)$ (or $\widehat{U}^P_{\mathcal{M}_i}(\cdot), \widehat{U}^P_{\mathbb{S}_{\mathcal{M}_i}}(\cdot)$) are obtained by maximizing $\varkappa^S$, (or $\varkappa^P$) and the $\alpha^S_{\mathcal{M}_i}$ (or $\alpha^P_{\mathcal{M}_i}$) value is given. Finally, $\alpha_{\mathcal{M}_i}$ and $\alpha_{\mathbb{S}_{\mathcal{M}_i}}$ values for the $\mathbb{G}^{\mathcal{M}_i}_{\mathcal{S}}$ game are decided as follows:

$$\alpha_{\mathcal{M}_i} = \frac{\alpha^S_{\mathcal{M}_i} + \alpha^P_{\mathcal{M}_i}}{2} \text{ and } \qquad \alpha_{\mathbb{S}_{\mathcal{M}_i}} = \left(1 - \alpha_{\mathcal{M}_i}\right). \tag{12}$$

To decide the $\beta_{\mathcal{S}_j}$ value in $\mathcal{S}_j$, we construct the $\mathbb{G}_{\mathcal{S}_j}$ game. In this game, $\mathbb{D}_e^{\mathcal{S}_j}$ and $\mathbb{D}_c^{\mathcal{S}_j}$ are the game players, and they are interacting sequentially to reach a mutual consensus. In this case, *SRS* is preferred for the solution concept. Through the interactive process, the utility functions of $\mathbb{D}_e^{\mathcal{S}_j}$ and $\mathbb{D}_c^{\mathcal{S}_j}$, i.e., $\mathcal{U}_e^{\mathcal{S}_j}(\cdot)$ and $\mathcal{U}_c^{\mathcal{S}_j}(\cdot)$, are defined as follows:

$$\begin{cases} \mathcal{U}_e^{\mathcal{S}_j}\left(\mathfrak{R}^e_{\mathbb{S}_{\mathcal{M}_i}}, \beta_{\mathcal{S}_j}\right) = \exp\left(\kappa \times \dfrac{\min\left(\mathfrak{R}^e_{\mathbb{S}_{\mathcal{M}_i}}, \left(\beta_{\mathcal{S}_j} \times \alpha_{\mathcal{M}_i} \times \mathfrak{M}_{\mathcal{M}_i}\right)\right)}{\mathfrak{R}^e_{\mathbb{S}_{\mathcal{M}_i}}}\right) - 1, \\ \mathcal{U}_c^{\mathcal{S}_j}\left(\mathfrak{R}^c_{\mathbb{S}_{\mathcal{M}_i}}, \beta_{\mathcal{S}_j}\right) = \varepsilon \times \log\left(1 - \left(\xi \times \dfrac{\min\left(\mathfrak{R}^c_{\mathbb{S}_{\mathcal{M}_i}}, \left(\left(1 - \beta_{\mathcal{S}_j}\right) \times \alpha_{\mathcal{M}_i} \times \mathfrak{M}_{\mathcal{M}_i}\right)\right)}{\mathfrak{R}^c_{\mathbb{S}_{\mathcal{M}_i}}}\right)\right), \end{cases} \tag{13}$$

where κ is a control parameter for the $\mathcal{U}_e^{\mathcal{S}_j}(\cdot)$, and ε, ξ are the control parameters for $\mathcal{U}_c^{\mathcal{S}_j}(\cdot)$. $\mathfrak{R}^e_{\mathbb{S}_{\mathcal{M}_i}}$ and $\mathfrak{R}^c_{\mathbb{S}_{\mathcal{M}_i}}$ are total requested resource amounts from $\mathbb{D}_e^{\mathcal{S}_j}$ and $\mathbb{D}_c^{\mathcal{S}_j}$, respectively. Based on the gradual negotiation, the *SRS* for the $\mathbb{G}_{\mathcal{S}_j}$ game, i.e., $m^{\mathrm{SRS}}(\mathbb{G}_{\mathcal{S}_j})$, converges to a fair-efficient solution while maintaining the viewpoints of $\mathbb{D}_e^{\mathcal{S}_j}$ and $\mathbb{D}_c^{\mathcal{S}_j}$. It is obtained as follows:

$$\begin{aligned} m^{SRS}\left(\mathbb{G}_{\mathcal{S}_j}\right) &= \left(\widehat{m}_e^{\mathcal{S}_j}, \widehat{m}_c^{\mathcal{S}_j}\right) \coloneqq \lim_{k \in \mathcal{N}} m_k^{SRS} \\ &= \left(\frac{1}{2} \times \left[\left(f_e^{\mathcal{S}_j}\left(m_{k-1,c}^{\mathcal{S}_j}\right), m_{k-1,c}^{\mathcal{S}_j}\right) + \left(m_{k-1,e}^{\mathcal{S}_j}, f_c^{\mathcal{S}_j}\left(m_{k-1,e}^{\mathcal{S}_j}\right)\right)\right]\right), \\ \text{s.t.,} &\begin{cases} f_e^{\mathcal{S}_j}\left(m_c^{\mathcal{S}_j}\right) = \mathbf{max}_{m_e^{\mathcal{S}_j}} \left(m_e^{\mathcal{S}_j} - d_e\right) \bullet l_s\left(m_e^{\mathcal{S}_j}, m_c^{\mathcal{S}_j}\right), \\ f_c^{\mathcal{S}_j}\left(m_e^{\mathcal{S}_j}\right) = \mathbf{max}_{m_c^{\mathcal{S}_j}} \left(m_c^{\mathcal{S}_j} - d_c\right) \bullet l_s\left(m_e^{\mathcal{S}_j}, m_c^{\mathcal{S}_j}\right), \\ m_0^{\mathcal{S}_j} \coloneqq \left(m_{0,e}^{\mathcal{S}_j}, m_{0,c}^{\mathcal{S}_j}\right) = \left(d_e, d_c\right) = d, \end{cases} \end{aligned} \tag{14}$$

where d_e and d_c are the disagreement points for $\mathbb{D}_e^{\mathcal{S}_j}$ and $\mathbb{D}_c^{\mathcal{S}_j}$, respectively. When the change between $m_{k-1,e}^{\mathcal{S}_j}$ and $m_{k,e}^{\mathcal{S}_j}$ is within a predefined minimum bound (φ), this change can be negligible. At this time, we can think that we converge a fair-efficient solution, and our negotiation process is terminated. Finally, we can get the $\beta_{\mathcal{S}_j}$ value, and the $(\alpha_{\mathcal{M}_i} \times \mathfrak{M}_{\mathcal{M}_i})$ resource amount is proportionally distributed based on $\beta_{\mathcal{S}_j}$.

For the devices in $\mathbb{D}$, the $\mathbb{G}_{\mathcal{D}}$ game is designed to distribute the assigned resource. In $\mathcal{M}_i$, each individual device belongs to one of $\mathbb{D}_{\mathcal{M}_i}$, $\mathbb{D}_e^{\mathcal{S}_j}$, and $\mathbb{D}_c^{\mathcal{S}_j}$ sets, where $\mathbb{D}_{\mathcal{M}_i} \cap \mathbb{D}_e^{\mathcal{S}_j} \cap \mathbb{D}_c^{\mathcal{S}_j} = \phi$. Devices in $\mathbb{D}_{\mathcal{M}_i}$, $\mathbb{D}_e^{\mathcal{S}_j}$, and $\mathbb{D}_c^{\mathcal{S}_j}$ operate the $\mathbb{G}_{\mathcal{D}}^{\mathcal{M}_i}$, $\mathbb{G}_e^{\mathcal{S}_j}$, and $\mathbb{G}_c^{\mathcal{S}_j}$ games separately, in a parallel manner. For $\mathcal{D}_k \in \left\{\mathbb{D}_{\mathcal{M}_i} \cup \mathbb{D}_e^{\mathcal{S}_j} \cup \mathbb{D}_c^{\mathcal{S}_j}\right\}$, its utility function is defined as follows:

$$\mathfrak{U}_{\mathcal{D}_k}\left(\mathfrak{R}_{\mathcal{D}_k}, \%\Gamma_{\mathcal{D}_k}\right) = \frac{\exp\left(\min\left(\mathfrak{R}_{\mathcal{D}_k}, \%\Gamma_{\mathcal{D}_k}\right)/\mathfrak{R}_{\mathcal{D}_k}\right) - \exp\left(-\min\left(\mathfrak{R}_{\mathcal{D}_k}, \%\Gamma_{\mathcal{D}_k}\right)/\mathfrak{R}_{\mathcal{D}_k}\right)}{\exp\left(\min\left(\mathfrak{R}_{\mathcal{D}_k}, \%\Gamma_{\mathcal{D}_k}\right)/\mathfrak{R}_{\mathcal{D}_k}\right) + \exp\left(-\min\left(\mathfrak{R}_{\mathcal{D}_k}, \%\Gamma_{\mathcal{D}_k}\right)/\mathfrak{R}_{\mathcal{D}_k}\right)}, \tag{15}$$

where $\mathfrak{R}_{\mathcal{D}_k}$ and $\%\Gamma_{\mathcal{D}_k}$ are the requested and allocated resource amounts for $\mathcal{D}_k$, respectively. Based on the corresponding devices, the $\mathbb{G}_{\mathcal{D}}^{\mathcal{M}_i}$, $\mathbb{G}_e^{\mathcal{S}_j}$, and $\mathbb{G}_c^{\mathcal{S}_j}$ games are operated in a distributed fashion. For $\mathbb{G}_{\mathcal{D}}^{\mathcal{M}_i}$, devices in the $\mathbb{D}_{\mathcal{M}_i}$ share the assigned resource, i.e., $(1-\alpha) \times \mathfrak{M}_{\mathcal{M}_i}$, according to the idea of KSS. Based on the utility function in (15), KSS, i.e.,

$X^{KSS}(\mathbb{G}_{\mathscr{D}}^{\mathscr{M}_i}) = (\ldots, \mathfrak{U}_{\mathscr{D}_k}^*(\mathfrak{R}_{\mathscr{D}_k}, \%\Gamma_{\mathscr{D}_k}^*), \ldots)$, is obtained as follows:

$$X^{\mathrm{KSS}}\left(\mathbb{G}_{\mathscr{D}}^{\mathscr{M}_i}\right) = \max_{\mathfrak{U}} \left\{ \mathscr{D}_k, \mathscr{D}_l \in \mathbb{D}_{\mathscr{M}_i} \middle| \frac{\mathfrak{U}_{\mathscr{D}_k}^*(\cdot) - d_{\mathscr{D}_k}}{\mathscr{I}_{\mathscr{D}_k} - d_{\mathscr{D}_k}} = \ldots = \frac{\mathfrak{U}_{\mathscr{D}_l}^*(\cdot) - d_{\mathscr{D}_l}}{\mathscr{I}_{\mathscr{D}_l} - d_{\mathscr{D}_l}} \right\},$$
$$\text{s.t.}, \sum_{\mathscr{D}_k \in \mathbb{D}_{\mathscr{M}_i}} \%\Gamma_{\mathscr{D}_k}^* \le \left(1 - \alpha_{\mathscr{M}_i}\right) \times \mathfrak{M}_{\mathscr{M}_i}, \tag{16}$$

where $\mathscr{I}_{\mathscr{D}_k}$ is the ideal outcome for the $\mathscr{D}_k$. For the $\mathbb{G}_e^{\mathscr{S}_j}$ and $\mathbb{G}_c^{\mathscr{S}_j}$ games, the utility function for each game player is defined as the same by using (15). Finally, devices in $\mathbb{D}_e^{\mathscr{S}_j}$ and $\mathbb{G}_c^{\mathscr{S}_j}$ share the assigned resources, i.e., $(\alpha \times \beta \times \mathfrak{M}_{\mathscr{M}_i})$ and $[(1 - (\alpha \times \beta)) \times \mathfrak{M}_{\mathscr{M}_i}]$, respectively, as the same manner as the $\mathbb{G}_{\mathscr{D}}^{\mathscr{M}_i}$ game.

4.4. Main Steps of Our Hierarchical Joint Cooperative Game Algorithm. By deploying different network infrastructures, such as MBSs and dense deployment of SBSs, the HetNet platform for IoT paradigm is widely seen as a solution for the 5G mobile networks. However, the performance of SBSs could be impacted by the interference from the MBS. To protect the SBS transmissions by mitigating the MBS interference, the eICIC technology is introduced. In this study, we design a hierarchical game model for the eICIC-based HetNet system. Our proposed game consists of different cooperative games such as $\mathbb{G}_{\mathscr{S}}^{\mathscr{M}}$, $\mathbb{G}_{\mathscr{S}}$, and $\mathbb{G}_{\mathscr{D}}$. In these games, game players can obtain, through cooperation, better outcomes than those obtained when they do not cooperate. The $\mathbb{G}_{\mathscr{S}}^{\mathscr{M}}$, $\mathbb{G}_{\mathscr{S}}$, and $\mathbb{G}_{\mathscr{D}}$ games are operated in a distributed parallel fashion according to *MCKSS*, *SRS*, and *KSS*. In dynamically changing HetNet system environments, our joint control paradigm is especially appropriate to negotiate conflicting requirements. The primary steps of the proposed scheme are described as follows:

Step 1: To carry out the simulation analysis, the parameter and control factor settings are shown in Table 2. Our simulation scenario is described in Section 5.

Step 2: At a sequence of time steps, the $\mathbb{G}_{\mathscr{S}}^{\mathscr{M}}$, $\mathbb{G}_{\mathscr{S}}$, and $\mathbb{G}_{\mathscr{D}}$ games are operated sequentially and interactively to reach a mutually consensus.

Step 3: First, the $\mathbb{G}_{\mathscr{S}}^{\mathscr{M}}$ game is designed as a two-player game with two decision criteria. In this game, $\mathscr{M}$ and $\mathbb{S}_{\mathscr{M}}$ are game players, and their utility functions are defined using (9) and (10).

Step 4: For the $\mathbb{G}_{\mathscr{S}}^{\mathscr{M}}$ game, MCKSS is adopted as a solution; it is obtained based on the equations (5) and (11). Finally, the $\alpha_{\mathscr{M}}$ value is calculated by using (12).

Step 5: Second, the $\mathbb{G}_{\mathscr{S}}$ game is designed as a single criterion two-player game. In this game, $\mathbb{D}_e^{\mathscr{S}}$ and $\mathbb{D}_c^{\mathscr{S}}$ are the game players, and their utility functions are defined using (13). For the $\mathbb{G}_{\mathscr{S}}$ game, the SRS is adopted as a solution. Finally, the $\beta_{\mathscr{S}}$ value is obtained based on the equations (5)–(7) and (14).

Step 6: Third, the $\mathbb{G}_{\mathscr{D}}$ game consists of three subgames such as $\mathbb{G}_{\mathscr{D}}^{\mathscr{M}_i}$, $\mathbb{G}_e^{\mathscr{S}_j}$, and $\mathbb{G}_c^{\mathscr{S}_j}$ games. For each game, devices in $\mathbb{D}_{\mathscr{M}}$, $\mathbb{D}_e^{\mathscr{S}}$, and $\mathbb{D}_c^{\mathscr{S}}$ are the game players, and their utility functions are defined using (15).

Step 7: For $\mathbb{G}_{\mathscr{D}}^{\mathscr{M}_i}$, $\mathbb{G}_e^{\mathscr{S}_j}$, and $\mathbb{G}_c^{\mathscr{S}_j}$ games, individual devices in $\mathbb{D}_{\mathscr{M}}$, $\mathbb{D}_e^{\mathscr{S}}$, and $\mathbb{D}_c^{\mathscr{S}}$ share the assigned resources based on KSS. Finally, $\%\Gamma_{\mathscr{D}_k}$ for each device is obtained based on equations (4) and (16).

Step 8: In our joint control approach, the $\mathbb{G}_{\mathscr{S}}^{\mathscr{M}}$, $\mathbb{G}_{\mathscr{S}}$, and $\mathbb{G}_{\mathscr{D}}$ games are sophisticatedly combined and work together to achieve reciprocal advantages.

Step 9: Constantly, individual MBS, SBSs, and IoT devices are self-monitoring the current eICIC-based HetNet system condition, and it proceeds to Step 2 for the next game iteration.

5. Performance Evaluation

This section presents the numerical results derived to validate the proposed method. By comparing with the existing RRS, DRA, and JAF schemes [13, 14, 15], we confirm that our approach outperforms other schemes via Matlab simulations. System parameters and their values are listed in Table 2, and the simulation environment and system scenario are given as follows [17, 18]:

(1) Simulated the eICIC-based HetNet system platform consists of five MBSs, twenty-five SBSs, and two-hundred fifty IoT devices, i.e., $|\mathbb{M}| = 5$, $|\mathbb{S}| = 25$, and $|\mathbb{D}| = 250$

(2) Each MBS has five SBSs, and IoT devices are randomly distributed over in the MBS covering area

(3) Each IoT device $\mathscr{D}_{1\le i\le l}$ generates six different type service requests ($\%\Gamma_{\mathscr{D}}$)

(4) The arrival process of $\%\Gamma_{\mathscr{D}}$ is the rate of the Poisson process (ρ). The offered range is varied from 0 to 3.0.

(5) The total spectrum resource of each MBS ($\mathfrak{M}_{\mathscr{M}}$) is 500 Gbps

(6) We assume the absence of physical obstacles in the network area

(7) The resource allocation process through the cooperative games is specified in terms of basic

Table 2: System parameters used in the simulation experiments.

Parameters	Value	Description
n	5	Total number of MBSs
m	25	Total number of SBSs
l	250	Total number of intelligent IoT devices
$\mathfrak{M}_{\mathcal{A}}$	500 Gbps	Wireless spectrum resource of each MBS
BAU	16 Mbps	The basic allocation unit for the resource allocation process
η, δ	0.15, 2	Control parameters for $U^{S}_{\mathcal{M}}(\cdot)$
ζ	9	A control parameter for $U^{P}_{\mathcal{M}}(\cdot)$
μ	0.9	A control parameters for $U^{S}_{\mathbb{S}_{\mathcal{M}}}$
ϱ, ω, ψ	2.2, 3, 0.5	Control parameters for $U^{P}_{\mathbb{S}_{\mathcal{M}}}(\cdot)$
κ	0.6	A control parameter for $\mathcal{U}^{\mathcal{S}}_{e}(\cdot)$
ε, ξ	−1.3, 0.8	Control parameters for $\mathcal{U}^{\mathcal{S}}_{c}(\cdot)$
φ	16 Mbps	The predefined minimum bound for SRS
Task type	Requested spectrum ($r_{\mathcal{M}}$)	Service duration (t)
I	256 Mbps	45 time-periods
II	640 Mbps	50 time-periods
III	192 Mbps	25 time-periods
IV	320 Mbps	15 time-periods
V	128 Mbps	40 time-periods
VI	384 Mbps	30 time-periods

allocation units (BAUs), where one BAU is 16 Mbps in this study

(8) The predefined minimum bound for the *SRS* is one BAU (16 Mbps)

(9) The disagreement points for cooperative games, i.e., d_i^S, d_i^P, d_e, and d_c, are zeros

(10) The eICIC-based HetNet system performance measures obtained on the basis of 100 simulation runs are plotted as functions of the Poisson process (ρ).

To evaluate the proposed scheme, we compare its performance in terms of system throughput, IoT device payoff, and fairness over offered service request generation ratios. Table 2 shows the control parameters and system factors used in the simulation.

Figure 3 shows the system throughput in the eICIC platform as a function of IoT device service request ratios. It is observed that our joint game approach consistently outperforms all other existing protocols. This is expected because when our proposed scheme is operated, the MBS SBSs, and devices work together to improve the resource efficiency. Especially, MCKSS is applied between the MBS and SBSs, SRS is adopted for each SBS's intraresource sharing process, and KSS is used to distribute the assigned resources for each device. Therefore, there will be more room to effectively exploit an available resource in order to maximize the overall system capacity. Based on the desirable features, our cooperative game model can guide selfish network agents to effectively share their limited resources in a coordinated manner. So, we can attain the highest system throughput among the four different schemes.

Figure 4 reports the normalized device payoff achieved by all considered schemes under different workload ratio. Compared with the other existing schemes, IoT devices in our proposed scheme adaptively share the resource in a step-by-step dynamic coordinated fashion. Finally, the assigned resource for each different device set is adaptively distributed based on the KSS; it ensures a fair-efficient solution for the resource allocation problem. Therefore, our approach is quite flexible to maximize the device payoff under widely different and diversified eICIC-based HetNet situations. Due to this reason, it can be seen that the proposed scheme achieves a higher device payoff over the existing RRS, DRA, and JAF protocols.

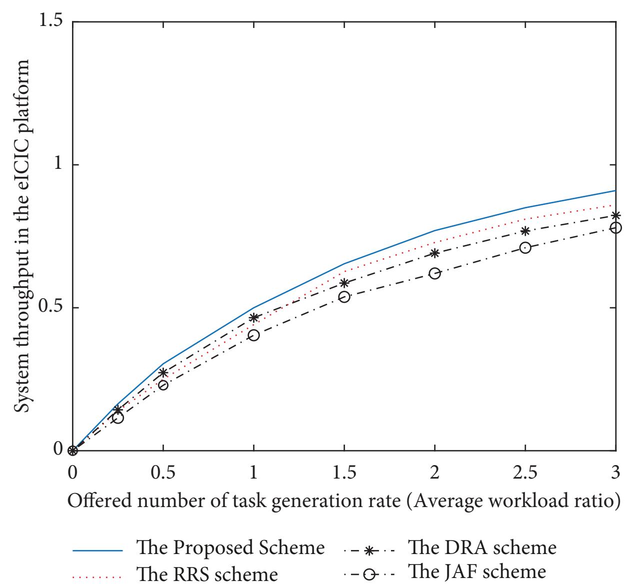

Figure 3: System throughput in the EICIC system.

For different protocols, the Jain's fairness index of IoT devices is shown in Figure 5. It can be used to evaluate the degree of fairness, and a larger Jain's index corresponds to a fairer allocation. As shown in Figure 5, our proposed scheme outperforms the RRS, DRA, and JAF protocols by

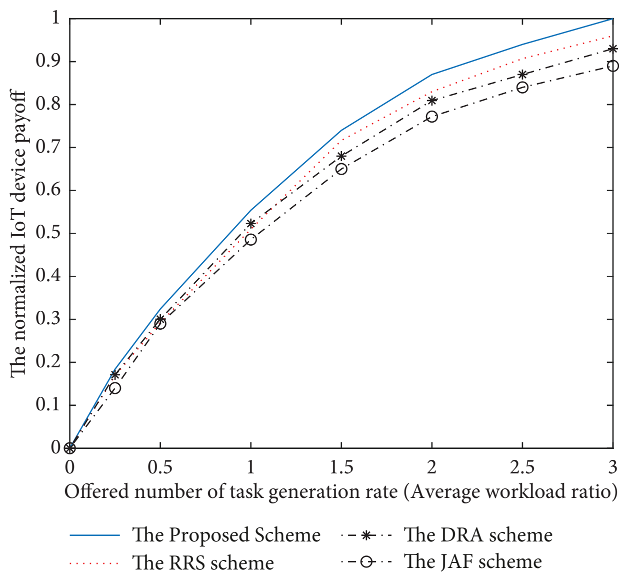

Figure 4: Normalized device payoff.

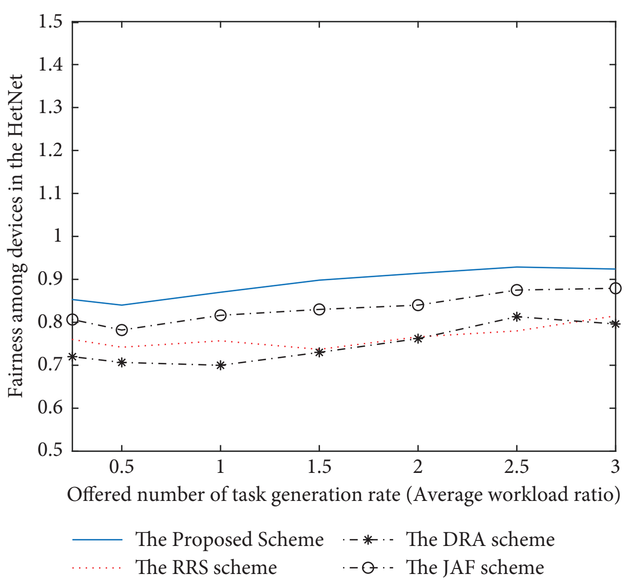

Figure 5: Fairness among devices in the eICIC system.

a large margin. In the proposed scheme, individual IoT devices can dynamically adjust their strategy through the cooperative game process, which is implemented as a hierarchical interactive manner. Therefore, IoT devices can collectively capture how to adapt their strategies to achieve the better benefit while getting reciprocal advantages. Therefore, all devices fairly share the limited resource in the eICIC-based HetNet system. Simulation results confirm the excellency of our proposed method for the fairness index; we maintain the highest fairness compared to other methods.

6. Summary and Conclusion

Traditionally, network traffic load in the cellular network varies continuously as a result of user mobility and traffic dynamics. The HetNet architecture is one of the most promising solutions to adaptively handle traffic fluctuations while enhancing the network coverage, spatial spectrum reuse, and system throughput. In this paper, we investigate a joint resource allocation scheme for the eICIC-based HetNet system, which offers several benefits, including a more equitable distribution of network traffic across the MBS and SBSs. For the eICIC technology, previous work did not consider dynamically changing network conditions in HetNets. Therefore, they studied the benefits of the eICIC-based HetNet with static optimization of eICIC parameters. Our proposed scheme is dynamic and can improve the system performance by using a hierarchical and repeated cooperative game model. Especially, we take into account both the ratio of non-ABS for MBS devices and the ratio of ABS fraction for SBS-extended devices. These ratios are adaptively adjusted based on the concept of MCKSS and SRS through the $\mathbb{G}_{\mathcal{S}}^{\mathcal{M}}$ and $\mathbb{G}_{\mathcal{S}}$ game models. And then, the assigned resources for MBS, SBS-centric, and SBS-extended devices are fair-efficiently distributed by using the idea of KSS through the $\mathbb{G}_{\mathcal{D}}$ game. By tightly coupling the $\mathbb{G}_{\mathcal{S}}^{\mathcal{M}}$, $\mathbb{G}_{\mathcal{S}}$, and $\mathbb{G}_{\mathcal{D}}$ games, we can lead to consensus outcomes that may be accepted by all IoT devices of MBS and SBSs. The main novelty of our joint game approach is to explore the reciprocal advantages through sequential interactions among the MBS, SBSs, and IoT devices. Under dynamically changing eICIC-based HetNet environments, our proposed scheme achieves a socially optimal solution in a step-by-step repeated manner. The extensive simulation results demonstrate the efficiency of the proposed algorithm and verify the superiority of our hierarchical control paradigm by comparing the existing RRS, DRA, and JAF schemes.

As a future work, we will study the concept of dual connectivity and joint association in the eICIC-based HetNet platform. Furthermore, it is interesting to formulate the resource allocation process as a multiobjective optimization problem. Moreover, we will take the ABS ratio issue to design a network-wide max-min fairness process and develop a new low complexity greedy algorithm based on the marginal utility. In addition, considering the privacy protected downlink and uplink decoupling is also an interesting research topic.

Data Availability

The data used to support the study are available from the corresponding author (swkim01@sogang.ac.kr).

Conflicts of Interest

The author, Sungwook Kim, declares that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

This research was supported by the MSIT (Ministry of Science and ICT), Korea, under the ITRC (Information Technology Research Center) support program (grant no. IITP-2023-2018-0-01799) supervised by the IITP

(Institute for Information & communications Technology Planning & Evaluation), and was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (grant no. 2021R1F1A1045472).

References

[1] Y. Xu, G. Gui, H. Gacanin, and F. Adachi, "A survey on resource allocation for 5G heterogeneous networks: current research, future trends, and challenges," *IEEE Communications Surveys & Tutorials*, vol. 23, no. 2, pp. 668–695, 2021.

[2] H. Lee, J. Park, S. H. Lee, and I. Lee, "Message-passing based user association and bandwidth allocation in HetNets with wireless backhaul," *IEEE Transactions on Wireless Communications*, vol. 22, no. 1, pp. 704–717, 2023.

[3] J. Li, X. Wang, Z. Li, H. Wang, and L. Li, "Energy efficiency optimization based on eICIC for wireless heterogeneous networks," *IEEE Internet of Things Journal*, vol. 6, no. 6, pp. 10166–10176, 2019.

[4] S. Vasudevan, R. N. Pupala, and K. Sivanesan, "Dynamic eICIC-a proactive strategy for improving spectral efficiencies of heterogeneous lte cellular networks by leveraging user mobility and traffic dynamics," *IEEE Transactions on Wireless Communications*, vol. 12, no. 10, pp. 4956–4969, 2013.

[5] D. Marabissi, G. Bartoli, R. Fantacci, and M. Pucci, "An optimized CoMP transmission for a heterogeneous network using eICIC approach," *IEEE Transactions on Vehicular Technology*, vol. 65, no. 10, pp. 8230–8239, 2016.

[6] A. Li and L. Qiu, "Resource allocation in heterogeneous networks with eICIC," in *Proceedings of the IEEE 2014 Sixth International Conference on Wireless Communications and Signal Processing (WCSP)*, pp. 1–6, Hefei, China, October 2014.

[7] W. Tang, R. Zhang, Y. Liu, and S. Feng, "Joint resource allocation for eICIC in heterogeneous networks," in *Proceedings of the IEEE Globecom'2014*, pp. 1–6, Austin, TX, USA, December 2014.

[8] J. Wang, Y. Hong, J. Wang et al., "Cooperative and competitive multi-agent systems: from optimization to games," *IEEE/CAA Journal of Automatica Sinica*, vol. 9, no. 5, pp. 763–783, 2022.

[9] S. Kim, "Multi-agent learning and bargaining scheme for cooperative spectrum sharing process," *IEEE Access*, vol. 11, pp. 47863–47872, 2023.

[10] S. Kim, *Game Theory Applications in Network Design*, IGI Global, Hershey, PA, USA, 2014.

[11] L. Monroy, A. M. Mármol, and V. Rubiales, "A bargaining model for finite n-person multi-criteria games," *International Game Theory Review*, vol. 11, no. 2, pp. 121–139, 2009.

[12] A. Diskin, M. Koppel, and D. Samet, "Generalized Raiffa solutions," *Games and Economic Behavior*, vol. 73, no. 2, pp. 452–458, 2011.

[13] W. Trockel, "Axiomatization of the discrete Raiffa solution," *Economic Theory Bulletin*, vol. 3, no. 1, pp. 9–17, 2015.

[14] S. Deb, P. Monogioudis, J. Miernik, and J. P. Seymour, "Algorithms for enhanced inter-cell interference coordination (eICIC) in LTE HetNets," *IEEE/ACM Transactions on Networking*, vol. 22, no. 1, pp. 137–150, 2014.

[15] Y. Shi, H. Qu, and J. Zhao, "Dual-connectivity enabled resource allocation approach with eICIC for throughput maximization in HetNets with backhaul constraint," *IEEE Wireless Communications Letters*, vol. 8, no. 4, pp. 1297–1300, 2019.

[16] Y. Jia, M. Zhao, and W. Zhou, "Joint user association and eICIC for max-min fairness in HetNets," *IEEE Communications Letters*, vol. 20, no. 3, pp. 546–549, 2016.

[17] S. Kim and P. K. Varshney, "An integrated adaptive bandwidth-management framework for QoS-sensitive multimedia cellular networks," *IEEE Transactions on Vehicular Technology*, vol. 53, no. 3, pp. 835–846, 2004.

[18] S. Kim, "Learning based bandwidth management algorithms by using bargaining and fictitious play approaches," *Computer Networks*, vol. 73, pp. 15–21, 2014.