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RESEARCH

A new fair-efficient spectrum allocation scheme for the LTE and WiFi coexistence platform

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Abstract

Long-term evolution (LTE) carrier aggregation with the unlicensed WiFi spectrum band has been pointed out as a good solution to handle the rapidly increasing wireless data traffic amounts. With both LTE and WiFi networks, the investigation of their coexistence is a hot research topic of active interest, primarily driven by industry and academia. In this study, we investigate a new spectrum allocation scheme for the LTE/WiFi coexistence platform. To maximize the system throughput while guaranteeing a relative fairness between heterogeneous networks, we adopt the cooperative game paradigm to design our novel scheme. According to the basic ideas of *Proportional Nash bargaining solution* (*PNBS*) and *Zhang's group bargaining solution* (*ZGBS*), we can leverage a mutual consensus to provide a fair-efficient solution for the LTE/WiFi spectrum sharing problem. Based on the online interactive bargaining approach, network agents work together to effectively share the LTE and WiFi spectrum resources. Under dynamically changing network environments, it is an essential approach to find the relevant trade-off between conflicting requirements, i.e., fairness and efficiency. Validated by simulation results, our proposed scheme can provide important insights into the LTE/WiFi system operations. Finally, we forecast further research trends on the basis of our conclusion.

Keywords: LTE/WiFi coexistence, Spectrum allocation, Proportional Nash bargaining solution, Group bargaining solution, Interactive bargaining game

1 Introduction

The global mobile traffic is expected to increase exponentially because of the explosive growth of mobile devices and emerging mobile applications. In particular, nearly two-thirds of the global population will have Internet access by 2023. The number of Internet of things (IoT) devices will be more than three times the global population by 2023. There will be 3.6 IoT devices per capita by 2023, up from 2.4 IoT devices per capita in 2018. There will be 29.3 billion IoT devices by 2023, up from 18.4 billion in 2018. However, it is hard to further improve the capacity of existing cellular networks, due to the lack of dedicated spectra. To address the spectrum scarcity and rapidly growing demand for wireless data communications, academia and industry have recently turned their attentions toward utilizing the unlicensed spectrum. In this regard, a variant of long-term evolution (LTE) technology, called licensed-assisted access (LAA), has been proposed to provide enhanced LTE services by sharing the unlicensed 5 GHz band, which is mainly used by WiFi networks [1–3].

Originally, LAA technology has been introduced in 3GPP Release 13 as part of LTE-Advanced. By assuming the simultaneous use of LTE and IEEE 802.11 wireless local area networks, it exploits carrier aggregation to combine the licensed LTE bands and the unlicensed industrial, scientific and medical bands, such as 2.4 GHz and 5.1 GHz. According to recent performance evaluation studies, LAA technology is an appealing option for network operators while promising faster data rates and more responsive user experience. However, the LAA mechanism does not explicitly standardize the spectrum access procedure; it is left for vendors' implementations. One method of LAA spectrum access procedure is the listen-before-talk functionality (LBTF) based on the simple ALOHA protocol; several studies addressed various aspects of this method. However, the LBTF approach only satisfies the interference requirement, but it completely neglects the critical feature of LTE systems, such as strict quality of service (QoS) guarantees. For example, the LBTF employing approach cannot integrate some non-queue-based information and neglects the exploration for the network statistics in a large time scale [4].

To effectively control the shared spectrum, LAA-compatible LTE base station (BS) should be responsible for the fair spectrum sharing while ensuring QoS requirements for LAA connections. Schedule-based LAA connections can improve the spectrum usability to provide a higher system throughput and fairness between WiFi and LTE networks. However, several challenges remain to be dealt with when designing QoS-aware LAA connections. First, the protocol of LTE/WiFi coexistence framework needs to have a flexibility for meeting the QoS requirements. Such flexibility can be achieved through a mutually acceptable agreement. Second, the performance should be quantified to maximize the LTE network with protection to the WiFi network. However, owing to the heterogeneity of these two systems, it is difficult to combine them organically into a practical and harmonious coexistence mechanism. Finally, effective solutions should be developed to optimize the coupling parameters for the fair-efficient LTE/WiFi coexistence system [2, 4].

QoS policy helps to manage the network system capabilities and its resources to provide IoT services. It enables the service providers to provide the clear visibility of their services and performance. In addition, it also ensures the usability of services to end users. Based on the LTE/WiFi coexistence platform, QoS policy can be enforced between IoT service providers and end users to deal with the optimization of service quality. Usually heterogeneous IoT applications can be categorized into two service types according to their required (QoS), i.e., *best-effort services* (*BESs*) and *QoS-preferred services* (*QPSs*). *BESs* do not have strict QoS requirements and prefer to join the WiFi network because of the price-sensitivity. In contrast, *QPSs* strongly need their QoS guarantees by joining the LTE/WiFi system. Based on different characteristics, *QPSs* have a higher priority than *BESs* during service operations [2, 5].

Apparently, the LTE/WiFi system belongs to the class of heterogeneous networks; one network performance can be severely affected in the presence of the other network. Therefore, the main control issue of heterogeneous networks is closely associated with the resource's fair-sharing. In the LTE/WiFi system platform, it is important to design a coexistence control protocol which addresses both the inter-network fairness as well as the intra-network fairness for the *BESs* and *QPSs*. However, little consensus has been reached on this important matter with divergent views that break across pro-*BESs* or pro-*QPSs* lines. Therefore, the key technique to utilize the potential performance advantage lies in the reasonable allocation of LTE and WiFi spectrum resources. In this paper, we investigate the LTE/WiFi system infrastructure, and construct the most appropriate spectrum allocation scheme in a fair-efficient manner. This approach can maximize the LTE/WiFi system performance while ensuring a desirable service fairness under diversified traffic environments [3, 6].

1.1 Technical concepts

One of the most crucial concerns for the LTE/WiFi system is how to achieve a notion of fair-efficient spectrum sharing. However, achieving this control issue is extremely difficult, whereas each network agents are free to act in a selfish manner. Therefore, we need a new control paradigm to address the LTE/WiFi spectrum allocation problem. Game theory is a branch of mathematics devoted to studying interaction among rational and self-interested game players. Originally, game theory generalizes the decision-theoretic approach among competing players and produces optimal decision-making of independent and competing players in a strategic setting. As a special case of game theory, bargaining solutions can effectively motivate the game players to work together to maximize social welfare through cooperation. In 1950s, John F. Nash was a pioneer in the study of bargaining solutions, and published his bargaining idea, which is now known as the Nash bargaining solution. Even though Nash's idea is the founding stone of bargaining process, it has been quite controversial with some features. Since then, some bargaining solutions have been newly introduced to ensure desirable features [7].

In 2011, Y. Xu and N. Yoshihara have introduced the concept of *Proportional Nash bargaining solution* (*PNBS*). They define and study a new bargaining solution by employing the basic idea of classical Nash solution concept to make recommendations for nonconvex bargaining problems. The *PNBS* is a natural solution to reconcile the conflicting criteria such as efficiency and equity considerations. The *PNBS* approach to bargaining problems opens a new possibility of investigating bargaining solutions, which are based on sequential eliminations of certain alternatives in bargaining problems. Usually, *Efficiency*, *Anonymity* and *Scale Invariance* are standard axioms in the original Nash bargaining solutions. With these axioms, the *PNBS* has additional two axioms; (1) *Equity Principle*, which reflects an equity concern in making a solution recommendation for bargaining problems, and (2) *Weak Contraction Independence*, which is a familiar axiom used for characterizing the Kalai–Smorodinsky bargaining solution for nonconvex bargaining problems [9].

Presently, a conventional group structure can no more cover all the types of cooperative structures in practice, external cooperation between the groups also affects the payoff allocation between individual players. X. Zhang also proposed a new bargaining solution, called *Zhang's group bargaining solution* (*ZGBS*), for the group bargaining problem. In the *ZGBS*, groups of individual players bargain with each other, and a solution is obtained to solve the bargaining problem with group structure. In order to model a group as a bargaining unit, the preferences of groups are defined, and group bargaining process is utilized in a more cooperative manner. A similar bargaining solution concept for the same group bargaining problem was given by S. Chae. The mathematical presentations of his bargaining solution is quite different from the *ZGBS*. However, to the ultimate, these two solutions are equivalent, and the final outcomes are the same [10, 11].

1.2 Main contributions

The major goal of our proposed spectrum allocation scheme is to effectively share the limited LTE and WiFi spectrum resources while optimizing social welfare through the relative fairness. For satisfying this goal, multiple system agents should work together in a coordinated manner. In the proposed scheme, the basic ideas of *NBS*, *PNBS* and *ZGBS* are adopted to solve the spectrum allocation problem in the LTE/WiFi platform. To make the problem tractable, we decompose it into three sub-problems: the LTE spectrum partitioning problem, and the LTE/WiFi spectrum sharing problems. For the first sub-problem, the LTE and WiFi service providers act cooperatively with each other according to the *NBS*. For the second sub-problem, we develop the LTE spectrum sharing algorithm for the *QPSs* based on the *PNBS*. For the third sub-problem, the *BESs* and *QPSs* negotiate an agreement by using the idea of *ZGBS*. Under dynamically changing system conditions, control decisions in our proposed scheme are made adaptively in a real-time online manner, which is practical approach to be implemented for a real-world LTE/WiFi system.

1.3 Organization

The remainder of this study is organized as follows. The related work is briefly reviewed in Sect. 2. Section 3 establishes the LTE/WiFi platform and formulates bargaining game models based on the *NBS*, *PNBS* and *ZGBS*. Then, between LTE and WiFi networks, the spectrum partitioning and sharing problems are presented. In addition, to help readers understand better, our proposed scheme is explained in detail how to achieve a fair-efficient bargaining solution. In Sect. 4, the simulation results are presented to verify the effectiveness of our approach. Finally, the conclusions and possible plans for future work are drawn in Sect. 5.

2 Related work

The main goal of LAA technology is to increase the LTE system throughput but not to degrade the performance of the WiFi network. Several research papers have been published to improve the LTE/WiFi system performance. Concerning the literature on this topic, we list below a few details of the most recent and relevant papers that deal with the concept of LTE/WiFi coexistence. In [15], a novel non-orthogonal multiple access (NOMA) method is proposed to improve the performance of multi-user systems. In order to improve the outage probability and ergodic capacity of downlink NOMA multi-user systems, the proposed method is derived in scenarios of perfect and imperfect successive interference cancellation [15]. H. Na et al. propose a new inter-user interference cancellation scheme applicable to the users with the same number of transmit and receive antennas [16]. By summing the received signals for two symbol periods, this scheme can cancel inter-user interference and obtain a twofold diversity order. The paper [17] formulates a downlink heterogeneous ultra-dense network where a lot of small base stations are randomly deployed with macro-base stations based on the Poisson point process. By considering three fractional power control strategies, the coverage probability and its variance are derived, and analyzed through the area spectral efficiency and energy efficiency of the network [17].

The article [18] provides an overview of 5G new radio unlicensed (NR-U) technology and discusses open challenges to operate it in the presence of WiFi systems. Achieving harmonious NR-U/WiFi coexistence requires investigating many NR-U issues, including waveform design, multi-channel operation, frequency reuse, scheduling and hybrid automatic repeat request, as well as the initial access and discovery design [18]. V. Loginov et al. propose two novel channel access methods for NR-U, in which an NR-U base station randomly stops sending the reservation signal [19]. The key idea of these two methods is to detect and resolve collisions while improving the overall performance in coexistence scenarios. The paper [8] considers maximizing the total throughput of both downlink and uplink in NR-U by jointly optimizing the time and power allocation while ensuring fair coexistence with WiFi. The proposed method in [8] can realize throughput fairness with different WiFi payloads, maximum downlink power and maximum channel occupation times, and achieves the largest WiFi throughput [8].

In [2], the *QoS-Aware Resource Allocation* (*QARA*) scheme investigates the QoS-aware coexistence between the LTE system and the WiFi system. To enable the QoS-awareness, system throughput and delay are quantified as the QoS metrics, and the QoS-aware control problem has been formulated. Major goal of this problem is to support as many QoS-preferred users as possible in the LTE network while maintaining fair QoS guarantees for the WiFi system. To satisfy this goal, the QoS-aware control problem is decomposed into two sub-problems, the sum-power minimization problem and the user association problem. For the sum-power minimization problem, the deep-cut ellipsoid method is adopted to optimize the LTE transmission time, subcarrier assignment, and power allocation. For the user association problem, an efficient algorithm called successive user removal is proposed. Through simulations, the effectiveness of the *QARA* scheme has been demonstrated based on the tradeoff among different QoS metrics [2].

The *Licensed and Unlicensed Spectrum Aggregation* (*LUSA*) scheme is devoted to the licensed and unlicensed spectrum aggregation technology within the LTE/WiFi coexistence system [12]. The *LUSA* scheme consists of four main functionalities, such as carrier selection, listen-before-talk, discontinuous transmission, and transmit power control mechanisms. Then, an enhanced learning technique is devised for enhancing the spectrum exploitation and utilization from the unlicensed system. In addition, a double Q-learning algorithm is implemented to accommodate two Q-functions with a common reward function that is presented as the overall system throughput. By using this learning method, the channel occupancy time and the interference power level are jointly optimized for the efficiency of LTE/WiFi coexistence system. Simulation results are provided to reveal the benefit of *LUSA* scheme [12].

M. Maule et al. propose the *Delivering Fairness and QoS Guarantee* (*DFQG*) scheme to achieve a high degree of fairness between the LTE and WiFi connections as well as to provide QoS guarantees for the admitted LTE communication sessions [13]. The *DFQG* scheme is based on two key algorithms: (1) LAA connection admission control algorithm, and (2) adaptive duty cycle resource division algorithm. The first algorithm is designed for the fair resource allocation between the WiFi and LAA sessions while ensuring a higher system throughput for the admitted LTE connections. The second algorithm dynamically adjusts the duty cycle duration to meet the upper delay bound requirements of the LTE connections. To effectively implement these two algorithms, LAA base stations are assumed to monitor their shared channel environments by keeping track of the number of WiFi connections. To characterize the key performance trade-offs, authors develop a new analytical model, and comprehensively investigate the performance of the *DFQG* scheme [13].

Until now, some existing state-of-the-art research papers have proposed novel schemes for the LTE/WiFi system. They attempt to achieve the fair coexistence between LTE and WiFi networks while maximizing the system throughput. However, none of research literatures consider an interactive perspective of different network agents. In this study, we apply the basic ideas of *NBS*, *PNBS* and *ZGBS* to get a well-balanced system performance. Therefore, system agents sequentially negotiate with each other to reach a mutual consensus, which can guarantee to effectively share the limited LTE/WiFi spectrum resources. As far as we can gather, this is the first work that different bargaining concepts are selectively applied to the design of spectrum allocation algorithm in the LTE/WiFi system.

3 The proposed LTE/WiFi spectrum allocation algorithm

This section presents the LTE/WiFi system infrastructure and introduces the fundamental concepts of *NBS*, *PNBS* and *ZGBS*. Then, a new three-phase bargaining game model is formulated to focus on the coexistence of LTE and WiFi networks. Finally, the main steps of our proposed spectrum allocation algorithm are described.

3.1 LTE/WiFi platform and interactive bargaining game

In this study, a heterogeneous network platform is considered to establish the joint LTE/WiFi platform. We consider a coexisting network of one LTE-LAA macro-cell and multiple WiFi micro-cells, which are overlaid on the macro-cell coverage area, and they are operated by WiFi access points (APs), i.e., $\mathbb{W} = \{\mathcal{W}_1, \ldots, \mathcal{W}_m\}$. Due to the small coverage of the APs, interference among them is neglected. LTE base station ($\mathfrak{B}$) operates on a licensed spectrum band ($\mathcal{S}_{\mathfrak{B}}$) , while the $\mathcal{W}_{1\leq i\leq m}$ has its unlicensed spectrum band $\left(\mathcal{S}_{\mathcal{W}_i}\right)$. The $\mathfrak{B}$ and $\mathcal{W}_i$ are connected via optical fiber networks. We assume that there are a number of IoT devices, i.e., $\mathbb{D} = \{\mathcal{D}_1, \ldots, \mathcal{D}_n\}$, which are located in the coverage region of the LTE/WiFi network system. The traffic services of these devices are either served by the $\mathfrak{B}$ or offloaded to the corresponding AP. It is assumed that the association among $\mathfrak{B}$, $\mathcal{W}_{1\leq i\leq m}$ and $\mathcal{D}_{1\leq j\leq n}$ has already been determined. The LTE/WiFi combined network infrastructure is considered as shown in Fig. 1, and Table 1 lists the mathematical notations used in this paper [14].

Individual IoT devices have been equipped with technology to enable them to connect simultaneously with the LTE and WiFi networks. Therefore, the collaboration between $\mathfrak{B}$ and $\mathcal{W}$ is realized by the dual connectivity capability, which enables IoT devices to aggregate the $\mathcal{S}_{\mathfrak{B}}$ and $\mathcal{S}_{\mathcal{W}}$ spectrum resources. According to a Poisson process, individual IoT devices in the $\mathbb{D}$ generate their communication tasks. In the coverage area of $\mathcal{W}_i$,

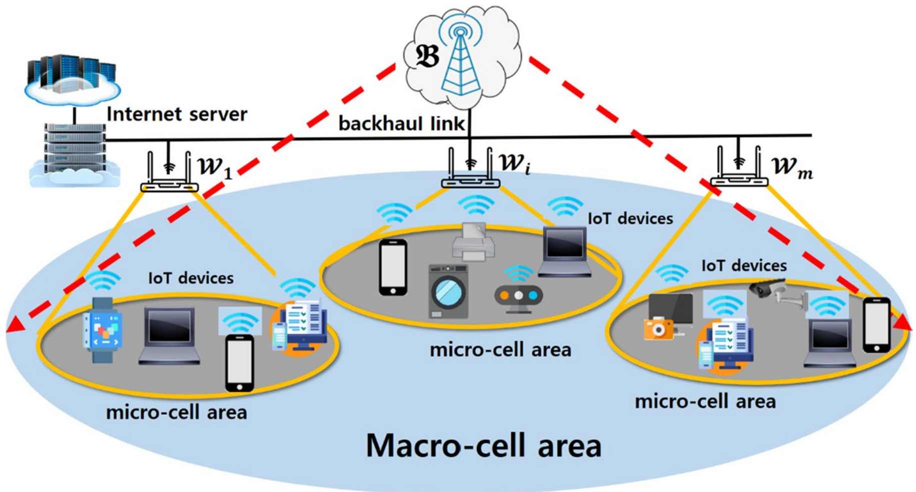

Fig. 1 LTE/WiFi platform architecture. In this study, the LTE/WiFi platform architecture stem consist of multiple smart devices, which is denoted as the set of IoT devices

Table 1 Symbols and parameters for mathematical formulations

Parameters	Explanations
$\mathcal{A}_{\mathcal{D}}$	The totally allocated spectrum resource for the $\mathcal{D}$
$\mathcal{A}_{\mathcal{D}}^{\mathfrak{B}}$	The $\mathcal{D}$'s LTE spectrum amount
$\mathcal{A}_{\mathcal{D}}^{\mathcal{W}}$	The $\mathcal{D}$'s WiFi spectrum amount
$\mathfrak{B}$	The LTE base station
$\mathbb{B}_{\mathcal{W}}$	The $\mathcal{W}$'s IoT devices generated *BESs*
$\mathbb{D}$	The set of IoT devices
$\mathcal{D}_{1 \le j \le n}$	The *j*th IoT device
$\mathbb{G}_{\mathfrak{B}}$	The second phase bargaining game
$\mathbb{G}_{\mathcal{W}}^{\mathfrak{B}}$	The first phase bargaining game
$\mathbb{G}_{\mathcal{W}}$	The third phase bargaining game
$\mathcal{J}_{\mathcal{D}}$	The $\mathcal{D}$'s strategy in the $\mathbb{G}_{\mathcal{W}}$
$\mathfrak{M}_{\mathfrak{B}}^{t}$	Total sum of $\mathcal{T}_{\mathcal{D}}$ where $\mathcal{D} \in \mathbb{Q}_{\mathfrak{B}}$
$\mathfrak{M}_{\mathcal{W}}^{t}$	Total sum of $\mathcal{T}_{\mathcal{D}}$ where $\mathcal{D} \in \mathbb{B}_{\mathcal{W}}$
$\mathcal{R}_{\mathfrak{B}}$	The $\mathfrak{B}$'s part of the $\mathcal{S}_{\mathfrak{B}}$
$\mathcal{R}_{\mathcal{W}}$	The $\mathcal{W}$'s part of the $\mathcal{S}_{\mathfrak{B}}$
$\Upsilon_{\mathcal{D}}$	The $\mathcal{D}$'s strategy to share the $\mathcal{R}_{\mathfrak{B}}$ in the $\mathbb{G}_{\mathfrak{B}}$
$\mathcal{S}_{\mathfrak{B}}$	The licensed spectrum band of $\mathfrak{B}$
$\mathcal{S}_{\mathcal{W}}$	The unlicensed spectrum band of $\mathcal{W}$
$\mathcal{T}_{\mathcal{D}}$	The $\mathcal{D}$'s maximum spectrum requirement
$\mathfrak{U}_{\mathfrak{B}}(\cdot)$	The $\mathfrak{B}$'s utility function in the $\mathbb{G}_{\mathcal{W}}^{\mathfrak{B}}$
$\mathfrak{U}_{\mathcal{W}}(\cdot)$	The $\mathcal{W}$'s utility function in the $\mathbb{G}_{\mathcal{W}}^{\mathfrak{B}}$
$U_{\mathcal{D}}(\cdot)$	The $\mathcal{D}$'s utility function in the $\mathbb{G}_{\mathcal{W}}^{\mathfrak{B}}$ game
$\mathcal{U}_{\mathcal{D}}^{BES}(\cdot)$	The $\mathcal{D}$'s utility function of *BES* in the $\mathbb{G}_{\mathcal{W}}$
$\mathcal{U}_{\mathcal{D}}^{QPS}(\cdot)$	The $\mathcal{D}$'s utility function of *QPS* in the $\mathbb{G}_{\mathcal{W}}$
$\mathbb{Q}_{\mathfrak{B}}$	All IoT devices, which generate *QPSs*
$\mathbb{Q}_{\mathcal{W}}$	The $\mathcal{W}$'s IoT devices generated *QPSs*
$\mathbb{W}$	The set of WiFi access points
$\mathcal{W}_{1 \le i \le m}$	The *i*th WiFi access point

we consider two different device sets. The set $\mathbb{B}_{\mathcal{W}_i}$ consists of devices, which generate *BESs* and the set of $\mathbb{Q}_{\mathcal{W}_i}$ consists of devices, which generate *QPSs*. These all devices can contact simultaneously to the $\mathfrak{B}$ and their corresponding $\mathcal{W}$ to share the $\mathcal{S}_{\mathfrak{B}}$ and $\mathcal{S}_{\mathcal{W}_i}$. If the $\mathcal{D}_j$ is in the $\mathcal{W}_i$'s area, the totally allocated spectrum resource for the $\mathcal{D}_j$ is $\mathcal{A}_{\mathcal{D}_j} = \mathcal{A}_{\mathcal{D}_j}^{\mathfrak{B}} + \mathcal{A}_{\mathcal{D}_j}^{\mathcal{W}_i}$ where $\mathcal{A}_{\mathcal{D}_j}^{\mathfrak{B}}$ and $\mathcal{A}_{\mathcal{D}_j}^{\mathcal{W}_i}$ are the $\mathcal{D}_j$'s LTE and WiFi spectrum amounts, respectively. The operational timeline is discretized into time slots to make spectrum allocation; it is the same time scale of communication task arrivals, which is a common assumption in the LTE/WiFi system [7].

In the LTE/WiFi system, the $\mathcal{S}_{\mathfrak{B}}$ and $\mathcal{S}_{\mathcal{W}_i}$ are limited resources. Therefore, effective spectrum allocation strategies should be considered to improve the system performance. To address the $\mathcal{S}_{\mathfrak{B}}$ and $\mathcal{S}_{\mathcal{W}_i}$ sharing problem, we formulate three bargaining games, i.e., $\mathbb{G}_{\mathcal{W}}^{\mathfrak{B}}$, $\mathbb{G}_{\mathfrak{B}}$ and $\mathbb{G}_{\mathcal{W}_i}$, at each time period. It is noteworthy that these three bargaining games formulate the $\mathfrak{B}$-$\mathcal{W}$-$\mathcal{D}$ association in a cooperative manner. In the $\mathbb{G}_{\mathcal{W}}^{\mathfrak{B}}$, the $\mathcal{S}_{\mathfrak{B}}$ is divided for the $\mathfrak{B}$ and $\mathcal{W}_{1\leq i\leq m}$ using the idea of *NBS* where $\mathcal{R}_{\mathfrak{B}}$ for the $\mathfrak{B}$ and $\mathcal{R}_{\mathcal{W}_i}$ for the$\mathcal{W}_i$. In the $\mathbb{G}_{\mathfrak{B}}$, the all devices generated *QPSs* bargain with each other to share the $\mathcal{R}_{\mathfrak{B}}$ according to the *PNBS*. In the $\mathbb{G}_{\mathcal{W}_i}$, the devices in the $\mathbb{B}_{\mathcal{W}_i}$ and $\mathbb{Q}_{\mathcal{W}_i}$ bargain with each other to distribute the $\mathcal{R}_i$ and $\mathcal{S}_{\mathcal{W}_i}$ based on the *ZGBS*. The $\mathbb{G}_{\mathcal{W}}^{\mathfrak{B}}$, $\mathbb{G}_{\mathfrak{B}}$ and $\mathbb{G}_{\mathcal{W}_i}$ are operated sequentially in a step-by-step interactive fashion. Formally, we define the game entities, i.e., $\mathbb{G} = \left\{\mathbb{G}_{\mathcal{W}}^{\mathfrak{B}}, \mathbb{G}_{\mathfrak{B}}, \mathbb{G}_{\mathcal{W}_i}\right\} = \left\{\mathbb{W}, \mathbb{D}, \mathfrak{B}, \left\{\mathbb{G}_{\mathcal{W}}^{\mathfrak{B}} | \mathbb{Q}_{\mathfrak{B}}, \mathbb{B}_{\mathcal{W}_i}, \mathcal{W}_i \in \mathbb{W}, \mathcal{S}_{\mathfrak{B}}, \left(\mathcal{R}_{\mathfrak{B}}, \mathcal{R}_{\mathcal{W}_i}\right), \mathfrak{U}_{\mathfrak{B}}(\cdot), \mathfrak{U}_{\mathcal{W}_i}(\cdot)\right\}, \left\{\mathbb{G}_{\mathfrak{B}} | \mathbb{Q}_{\mathfrak{B}}, \mathcal{R}_{\mathfrak{B}}, \Upsilon_{\mathcal{D}_k \in \mathbb{Q}_{\mathfrak{B}}}, U_{\mathcal{D}_k}(\cdot)\right\}, \left\{\mathbb{G}_{\mathcal{W}_{1\leq i\leq m}} | \mathcal{W}_i, \mathcal{D}_j \in \left(\mathbb{B}_{\mathcal{W}_i} \cup \mathbb{Q}_{\mathfrak{B}}\right), \mathcal{R}_{\mathcal{W}_i}, \mathcal{S}_{\mathcal{W}_i}, \mathcal{J}_{\mathcal{D}_j}, \mathcal{U}_{\mathcal{D}_j}^{QPS}(\cdot), \mathcal{U}_{\mathcal{D}_j}^{BES}(\cdot)\right\}, T\right\}$ of gameplay.

- The $\mathbb{G}_{\mathcal{W}}^{\mathfrak{B}}$, $\mathbb{G}_{\mathfrak{B}}$ and $\mathbb{G}_{\mathcal{W}_i}$ are mutually and reciprocally interdependent in an interactive manner, and they work together to share the $\mathcal{S}_{\mathfrak{B}}$ and $\mathcal{S}_{\mathcal{W}_i}$.
- $\mathbb{Q}_{\mathcal{W}_i}$ and $\mathbb{B}_{\mathcal{W}_i}$ are the sets of IoT devices, which are covered by the $\mathcal{W}_i$ and generate *QPSs* and *BESs*, respectively. $\mathbb{Q}_{\mathfrak{B}}$ is the set of all IoT devices, which generate *QPSs* where $\mathbb{Q}_{\mathfrak{B}} = \bigcup_{\mathcal{W}_i \in \mathbb{W}} \mathbb{Q}_{\mathcal{W}_i}$.
- In the $\mathbb{G}_{\mathcal{W}}^{\mathfrak{B}}$, the $\mathfrak{B}$ and $\mathcal{W}_{1\leq i\leq m}$ are game players, and $\mathcal{R}_{\mathfrak{B}}$, $\mathcal{R}_{\mathcal{W}_i}$ are their strategies. For the $\mathfrak{B}$ and $\mathcal{W}_i$, the $\mathfrak{U}_{\mathfrak{B}}(\cdot)$,$\mathfrak{U}_{\mathcal{W}_i}(\cdot)$ are their utility functions, respectively.
- In the $\mathbb{G}_{\mathfrak{B}}$, the device $\mathcal{D}_k \in \mathbb{Q}_{\mathfrak{B}}$ is a game player, and $\Upsilon_{\mathcal{D}_k}$ is its strategy to share the $\mathcal{R}_{\mathfrak{B}}$. $U_{\mathcal{D}_k}(\cdot)$ is the $\mathcal{D}_k$'s utility function.
- In the $\mathbb{G}_{\mathcal{W}_i}$, the $\mathcal{D}_j \in \left\{\mathbb{Q}_{\mathcal{W}_i} \cup \mathbb{B}_{\mathcal{W}_i}\right\}$ is a game player, and $\mathcal{J}_{\mathcal{D}_j}$ is its strategy. If $\mathcal{D}_j \in \mathbb{B}_{\mathcal{W}_i}\left(\text{ or } \mathcal{D}_j \in \mathbb{Q}_{\mathcal{W}_i}\right)$, $\mathcal{U}_{\mathcal{D}_j}^{BES}(\cdot)\left(\text{ or } \mathcal{U}_{\mathcal{D}_j}^{QPS}(\cdot)\right)$ is its utility function.
- 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 $\mathbb{G}_{\mathcal{W}}^{\mathfrak{B}}$, $\mathbb{G}_{\mathfrak{B}}$ and $\mathbb{G}_{\mathcal{W}_i}$.

3.2 The fundamental ideas of *PNBS* and *ZGBS*

To characterize the fundamental idea of *PNBS*, we assume an n-player bargaining problem. Let $N = \{1 \ldots i \ldots n\}$ be the set of players and $\mathbb{R}_+$ (or $\mathbb{R}_{++}$) is the set of all non-negative (*or* all positive) real numbers. Let $\mathbb{R}_+^n$ $\left(\text{ or } \mathbb{R}_{++}^n\right)$ be the n-fold Cartesian product of $\mathbb{R}_+$ (or $\mathbb{R}_{++}$). For any $x, y \in \mathbb{R}_+^n$, we write $x \geq y$ to mean $x_i \geq y_i$ for all $i \in N$. $x > y$ means $x_i \geq y_i$ for all $i \in N$ and $x \neq y$. $x \gg y$ means $x_i > y_i$ for all $i \in N$. For any subset $A \subseteq \mathbb{R}_+^n$, A is said to be i) *non-trivial* if there exists $a \in A$ such that $a \gg 0$, and ii) *comprehensive* if for all $x, y \in \mathbb{R}_+^n$, $x > y$ and $x \in A$ implies $y \in A$. Let

$\sum$ be the set of all *on-trivial*, *compact* and *comprehensive* subsets of $\mathbb{R}_+^n$. Elements in $\sum$ are interpreted as bargaining problems. Usually, a bargaining solution assigns a nonempty subset of A for every bargaining problem $A \in \sum$. For all $A \in \sum$ and all $i \in N$, let $m_i(A) = \max\{a_i|(a_1, \ldots a_i \ldots a_n) \in A\}$. Therefore, $m(A) \equiv (m_i(A))_{i \in N}$ is the ideal point of A. Let $d_{i \in N}$ be a disagree point, which is expected to be the result of non-cooperative actions; it means a failure of the bargaining process. If for all $A \in \sum$, Nash bargaining solution, i.e., $NBS\,(A)$, is defined by [9]:

$$NBS(A) = \prod_{i \in N} (a_i - d_i) \geq \prod_{i \in N} (x_i - d_i), \quad \text{s.t.,} \ a \in A \text{ and } x \in A \tag{1}$$

Based on the $NBS\,(A)$, the $PNBS$, i.e., $PNBS\,(A)$, is mathematically formulated as follows [9]:

$$PNBS(A) = \min_{i \in N} \left\{ \frac{a_i - d_i}{m_i(A) - d_i} \right\} \geq \min_{i \in N} \left\{ \frac{x_i - d_i}{m_i(A) - d_i} \right\}, \quad \text{s.t.,} \ a, x \in NBS(A) \tag{2}$$

To define the concept of $ZGBS$, the bargaining problem is represented as a quadruple $\{\Gamma, S, u, d\}$, where Γ is a partition of a player set $N = \{1 \ldots i \ldots n\}$ and each element in Γ represents a formed coalition.S is a feasible payoff set in $\mathbb{R}^{|N|}$ where $\mathbb{R}^{|N|}$ is the n-dimensional Euclidean space, and $|N|$ denotes its size. The $d \in \mathbb{R}^{|N|}$ is a disagreement payoff vector when the coalitions fail to reach any joint contracts. There exists at least one element $u \in S$ where $u_i > d_i$ for any $i \in N$; u_i represents the i's payoff. When Γ is the finest partition of N, the pure bargaining problem with a coalition structure is the original Nash's pure bargaining problem. The $ZGBS$ is a direct extension to Nash's solution. To express the $ZGBS$, a function for two payoff vectors u and v with $A \in \Gamma$, i.e., $f\,(u, v, A)$, is defined as [10]:

$$f\,(u, v, A) = \sum_{A \in \Gamma} \left(\frac{1}{|A|} \times \left(\sum_{i \in A} \frac{u_i - d_i}{v_i - d_i} \right) \right) \tag{3}$$

According to (3), the $ZGBS\,(\Gamma, S, u, d)$ is defined by [10]:

$$\begin{aligned} & ZGBS(\Gamma, S, u) := s^* = \max_{u \in S} f\left(u, s^*, A\right) = |\Gamma| \\ & \text{s.t.,} \ u \in S, u_i > d_i \text{ and } \forall i \in N \end{aligned} \tag{4}$$

In 2004, Chae and Heidhues proposed a new solution concept to the group bargaining problem. In their approach, groups of individual players bargain both within and across groups. It treats a bargaining group as one bargainer even in cases where the bargaining group consists of heterogeneous individuals. They also showed that their solution implies the joint-bargaining paradox, and specified a class of solutions in which a larger bargaining group is treated better. The Chae and Heidhues's solution constitutes a traditional Nash solution within as well as across groups; it is given by [11]:

$$\max_{u \in S} \prod_{j=1}^{k} \left(\prod_{i \in A_j} (u_i - d_i) \right), \quad \text{s.t., } A_j \in \Gamma = \{A_1, ..., A_k\} \tag{5}$$

Despite the difference in mathematical representations, the paper [10] has proved that the *ZGBS* and the Chae and Heidhues's solution become identical after applying a linear transformation to one problem. Therefore, they are equivalent in group bargaining problems [10].

3.3 The three-phase bargaining game in the LTE/WiFi platform

In the LTE/WiFi coexistent platform infrastructure, individual IoT devices generate their tasks. To effectively share the $\mathcal{S}_{\mathfrak{B}}$ and $\mathcal{S}_{\mathcal{W}}$ spectrum resources, three bargaining games $\mathbb{G}_{\mathcal{W}}^{\mathfrak{B}}$, $\mathbb{G}_{\mathfrak{B}}$ and $\mathbb{G}_{\mathcal{W}_i}$ are developed, and work together to allocate the $\mathcal{S}_{\mathfrak{B}}$ and $\mathcal{S}_{\mathcal{W}}$. At the first phase, the $\mathbb{G}_{\mathcal{W}}^{\mathfrak{B}}$ is designed to partition the $\mathcal{S}_{\mathfrak{B}}$ into $\mathcal{R}_{\mathfrak{B}}$ and $\mathcal{R}_{\mathcal{W}_{1\le i\le m}}$. For this partitioning problem, the $\mathfrak{B}$ and $\mathcal{W}_i$ bargain with each other based on the current information about *QPSs* and *BESs*. As game players, the utility functions for $\mathfrak{B}$ and $\mathcal{W}_i$ at time t_c, i.e., $\mathfrak{U}_{\mathfrak{B}}^{t_c}(\cdot)$ and $\mathfrak{U}_{\mathcal{W}_i}^{t_c}(\cdot)$, are defined as follows:

$$\begin{cases} \mathfrak{U}_{\mathfrak{B}}^{t_c}\left(\mathcal{S}_{\mathfrak{B}}, \mathcal{R}_{\mathfrak{B}}, \mathfrak{M}_{\mathfrak{B}}^{t_c}\right) = \log\left(\frac{\min(\mathcal{S}_{\mathfrak{B}}, \mathcal{R}_{\mathfrak{B}})}{\mathfrak{M}_{\mathfrak{B}}^{t_c}} + \eta\right) - exp\left(-\frac{\min(\mathcal{S}_{\mathfrak{B}}, \mathcal{R}_{\mathfrak{B}})}{\mathfrak{M}_{\mathfrak{B}}^{t_c}}\right) \\ \mathfrak{U}_{\mathcal{W}_i}^{t_c}\left(\mathcal{S}_{\mathfrak{B}}, \mathcal{S}_{\mathcal{W}_i}, \mathcal{R}_{\mathcal{W}_i}, \mathfrak{M}_{\mathcal{W}_i}^{t_c}\right) = \beta \times \left(\frac{\log\left(\frac{\min\left(\mathcal{S}_{\mathfrak{B}}, \mathcal{R}_{\mathcal{W}_i}\right) + \mathcal{S}_{\mathcal{W}_i}}{\mathfrak{M}_{\mathcal{W}_i}^{t_c}} + \kappa\right)}{\log\left(\frac{\min\left(\mathcal{S}_{\mathfrak{B}}, \mathcal{R}_{\mathcal{W}_i}\right) + \mathcal{S}_{\mathcal{W}_i}}{\mathfrak{M}_{\mathcal{W}_i}^{t_c}} + \omega\right)} \right) \end{cases}$$
$$\text{s.t., } \mathfrak{M}_{\mathfrak{B}}^{t_c} = \sum_{\mathcal{D}_k \in \mathbb{Q}_{\mathfrak{B}}} \mathcal{T}_{\mathcal{D}_k}, \mathfrak{M}_{\mathcal{W}_i}^{t_c} = \sum_{\mathcal{D}_j \in \mathbb{B}_{\mathcal{W}_i}} \mathcal{T}_{\mathcal{D}_j} \text{ and } \mathcal{S}_{\mathfrak{B}} = \mathcal{R}_{\mathfrak{B}} + \sum_{\mathcal{W}_i \in \mathbb{W}} \mathcal{R}_{\mathcal{W}_i} \tag{6}$$

where η is a control parameter for the $\mathfrak{U}_{\mathfrak{B}}^{t_c}(\cdot)$, and β, κ, ω are control parameters for the $\mathfrak{U}_{\mathcal{W}_i}^{t_c}(\cdot)$. $\mathcal{T}_{\mathcal{D}_k}$ is the $\mathcal{D}_k$'s maximum spectrum requirement. For the $\mathbb{G}_{\mathcal{W}}^{\mathfrak{B}}$, the features of *efficiency*, *anonymity* and *scale invariance* are important between *QPSs* and *BESs*. Therefore, the idea of classical *NBS* is adopted. In this study, the utilities of disagreement points are assumed as zeros, and $\left[\mathcal{R}_{\mathfrak{B}}, \mathcal{R}_{\mathcal{W}_1}, \ldots, \mathcal{R}_{\mathcal{W}_m}\right]$ is obtained as the *NBS* for the $\mathbb{G}_{\mathcal{W}}^{\mathfrak{B}}$; it is given by:

$$\begin{aligned} \underset{\left[\mathcal{R}_{\mathfrak{B}}, \mathcal{R}_{\mathcal{W}_1}, \ldots, \mathcal{R}_{\mathcal{W}_m}\right]}{NBS}\left(\mathfrak{U}_{\mathfrak{B}}^{t_c}(\cdot), \mathfrak{U}_{\mathcal{W}_{1\le i\le m}}^{t_c}(\cdot)\right) &= \left(\mathfrak{U}_{\mathfrak{B}}^{t_c}(\mathcal{R}_{\mathfrak{B}}) \times \prod_{\mathcal{W}_i \in \mathbb{W}} \mathfrak{U}_{\mathcal{W}_i}^{t_c}(\mathcal{R}_{\mathcal{W}_i})\right) \\ &\ge \left(\mathfrak{U}_{\mathfrak{B}}^{t_c}\left(\mathcal{R}_{\mathfrak{B}}^{'}\right) \times \prod_{\mathcal{W}_i \in \mathbb{W}} \mathfrak{U}_{\mathcal{W}_i}^{t_c}\left(\mathcal{R}_{\mathcal{W}_i}^{'}\right)\right) \end{aligned} \tag{7}$$

At the second phase, the $\mathbb{G}_{\mathfrak{B}}$ game is implemented to share the $\mathcal{R}_{\mathfrak{B}}$ among devices in the $\mathbb{Q}_{\mathfrak{B}}$. For the $\mathcal{D}_k \in \mathbb{Q}_{\mathfrak{B}}$, the utility function, i.e., $U_{\mathcal{D}_k}^{t_c}(\cdot)$, is defined as follows:

$$U_{\mathcal{D}_k}^{t_c}\left(\Upsilon_{\mathcal{D}_k},\mathcal{T}_{\mathcal{D}_k},\mathcal{R}_{\mathfrak{B}}\right)=\left(\frac{\exp\left(\frac{\Upsilon_{\mathcal{D}_k}}{\mathcal{T}_{\mathcal{D}_k}}\right)-\exp\left(-\frac{\Upsilon_{\mathcal{D}_k}}{\mathcal{T}_{\mathcal{D}_k}}\right)}{\exp\left(\frac{\Upsilon_{\mathcal{D}_k}}{\mathcal{T}_{\mathcal{D}_k}}\right)+\exp\left(-\frac{\Upsilon_{\mathcal{D}_k}}{\mathcal{T}_{\mathcal{D}_k}}\right)}\right)+\frac{\log\left(\frac{\Upsilon_{\mathcal{D}_k}}{\mathcal{T}_{\mathcal{D}_k}}+\psi\right)}{\log\left(\frac{\Upsilon_{\mathcal{D}_k}}{\mathcal{T}_{\mathcal{D}_k}}+\varrho\right)}$$
$$\text{s.t., } \mathcal{R}_{\mathfrak{B}}\geq\sum_{\mathcal{D}_k\in\mathbb{Q}_{\mathfrak{B}}}\Upsilon_{\mathcal{D}_k} \quad (8)$$

where ψ, ϱ are control parameters for the $U_{\mathcal{D}_k}^{t_c}(\cdot)$. To get a fair-efficient solution for *QPSs*, we concern the features of *equity principle* and *weak contraction independence*. Therefore, the *PNBS* is preferred for the solution concept of $\mathbb{G}_{\mathfrak{B}}$. As the *PNBS* for the $\mathbb{G}_{\mathfrak{B}}$, $\left[\ldots,\Upsilon_{\mathcal{D}_k\in\mathbb{Q}_{\mathfrak{B}}},\ldots\right]$ is obtained by:

$$\underset{\left[\ldots,\Upsilon_{\mathcal{D}_k\in\mathbb{Q}_{\mathfrak{B}}},\ldots\right]}{PNBS}\left(U_{\mathcal{D}_k\in\mathbb{Q}_{\mathfrak{B}}}^{t_c}(\cdot)\right)=\min_{\mathcal{D}_k}\left\{\frac{U_{\mathcal{D}_k}^{t_c}\left(\Upsilon_{\mathcal{D}_k}\right)}{m_{\mathcal{D}_k}\left(U_{\mathcal{D}_k}^{t_c}(\cdot)\right)}\right\}\geq\min_{\mathcal{D}_k}\left\{\frac{U_{\mathcal{D}_k}^{t_c}\left(\Upsilon_{\mathcal{D}_k}^{'}\right)}{m_{\mathcal{D}_k}\left(U_{\mathcal{D}_k}^{t_c}(\cdot)\right)}\right\}$$
$$\text{s.t., } \left[\ldots,\Upsilon_{\mathcal{D}_k\in\mathbb{Q}_{\mathfrak{B}}},\ldots\right]\in\prod_{\mathcal{D}_k\in\mathbb{Q}_{\mathfrak{B}}}U_{\mathcal{D}_k}^{t_c}\left(\Upsilon_{\mathcal{D}_k}\right)\geq\prod_{\mathcal{D}_k\in\mathbb{Q}_{\mathfrak{B}}}U_{\mathcal{D}_k}^{t_c}\left(\Upsilon_{\mathcal{D}_k}^{'}\right) \quad (9)$$

At the third phase, each $\mathcal{W}_i$ distributes its $\mathcal{R}_{\mathcal{W}_i}$ and $\mathcal{S}_{\mathcal{W}_i}$ for its corresponding device $\mathcal{D}_j\in\left\{\mathbb{B}_{\mathcal{W}_i}\cup\mathbb{Q}_{\mathcal{W}_i}\right\}$. During the $\mathbb{G}_{\mathcal{W}_i}$ game process, the $\mathcal{W}_i$ categorizes its corresponding devices into two groups, i.e., $\mathbb{B}_{\mathcal{W}_i}$ and $\mathbb{Q}_{\mathcal{W}_i}$, and the spectrum sharing problem in treated as the group bargaining problem. As a game player, the $\mathcal{D}_j$'s utility functions for *QPSs* and *BESs*, i.e., $\mathcal{U}_{\mathcal{D}_j}^{QPS}(\cdot)$ and $\mathcal{U}_{\mathcal{D}_j}^{BES}(\cdot)$, are defined as follows:

$$\begin{cases}\mathcal{U}_{\mathcal{D}_j}^{QPS}\left(\mathcal{J}_{\mathcal{D}_j},\mathcal{S}_{\mathcal{W}_i},\mathcal{R}_{\mathcal{W}_i},\mathcal{S}_{\mathcal{W}_i},\mathbb{B}_{\mathcal{W}_i},\mathbb{Q}_{\mathcal{W}_i}\right)= \\ \left(\frac{exp\left(\frac{\left(\mathcal{J}_{\mathcal{D}_j}+\Upsilon_{\mathcal{D}_j}\right)}{\mathcal{T}_{\mathcal{D}_j}}\right)-exp\left(-\frac{\left(\mathcal{J}_{\mathcal{D}_j}+\Upsilon_{\mathcal{D}_j}\right)}{\mathcal{T}_{\mathcal{D}_j}}\right)}{exp\left(\frac{\left(\mathcal{J}_{\mathcal{D}_j}+\Upsilon_{\mathcal{D}_j}\right)}{\mathcal{T}_{\mathcal{D}_j}}\right)+exp\left(-\frac{\left(\mathcal{J}_{\mathcal{D}_j}+\Upsilon_{\mathcal{D}_j}\right)}{\mathcal{T}_{\mathcal{D}_j}}\right)}\right)+\frac{\log\left(\frac{\left(\mathcal{J}_{\mathcal{D}_j}+\Upsilon_{\mathcal{D}_j}\right)}{\mathcal{T}_{\mathcal{D}_j}}+\psi\right)}{\log\left(\frac{\left(\mathcal{J}_{\mathcal{D}_j}+\Upsilon_{\mathcal{D}_j}\right)}{\mathcal{T}_{\mathcal{D}_j}}+\varrho\right)} \\ \mathcal{U}_{\mathcal{D}_j}^{BES}\left(\mathcal{J}_{\mathcal{D}_j},\mathcal{S}_{\mathcal{W}_i},\mathcal{R}_{\mathcal{W}_i},\mathcal{S}_{\mathcal{W}_i},\mathbb{B}_{\mathcal{W}_i},\mathbb{Q}_{\mathcal{W}_i}\right)=\frac{\alpha}{\xi+exp\left(-\frac{\mathcal{J}_{\mathcal{D}_j}}{\mathcal{T}_{\mathcal{D}_j}}\right)}-\tau\end{cases}$$
$$\text{s.t., } \left(\mathcal{R}_{\mathcal{W}_i}+\mathcal{S}_{\mathcal{W}_i}\right)\geq\sum_{\mathcal{D}_j\in\left\{\mathbb{B}_{\mathcal{W}_i}\cup\mathbb{Q}_{\mathcal{W}_i}\right\}}\mathcal{J}_{\mathcal{D}_j} \quad (10)$$

where ψ, ϱ are control parameters for the $\mathcal{U}_{\mathcal{D}_j}^{QPS}(\cdot)$; they are defined as the same in the $U_{\mathcal{D}_k}^{t_c}(\cdot)$. ξ,α,τ are control parameters for the $\mathcal{U}_{\mathcal{D}_j}^{BES}(\cdot)$. For the$\mathcal{D}_j$, $\mathcal{J}_{\mathcal{D}_j}$ is the allocated spectrum amount in the $\mathbb{G}_{\mathcal{W}_i}$ game. If $\mathcal{D}_j\in\mathbb{Q}_{\mathcal{W}_i}$, the $\mathcal{D}_j$ has already obtained the $\Upsilon_{\mathcal{D}_j}$ in the $\mathbb{G}_{\mathfrak{B}}$ game. In this case, the $\mathcal{J}_{\mathcal{D}_j}$ is additionally added, and the $\mathcal{D}_j$ has total $\left(\mathcal{J}_{\mathcal{D}_j}+\Upsilon_{\mathcal{D}_j}\right)$ spectrum amount for its *QPSs*. If $\mathcal{D}_j\in\mathbb{B}_{\mathcal{W}_i}$, the $\mathcal{D}_j$ gets the $\Upsilon_{\mathcal{D}_j}$ for its *BESs.* From the $\mathbb{G}_{\mathcal{W}_i}$, we can think the different type services, i.e., *BESs* and *QPSs*, are bargaining units. In this case, the *ZGBS* is preferred to reach a consensus in the $\mathbb{G}_{\mathcal{W}_i}$ game. It is given by:

$$ZGBS\left(\mathbb{B}_{\mathcal{W}_i},\mathbb{Q}_{\mathfrak{B}},\mathcal{U}_{\mathcal{D}_j\in\left\{\mathbb{B}_{\mathcal{W}_i}\cup\mathbb{Q}_{\mathcal{W}_i}\right\}}(\cdot)\right)=\max_{\left[\ldots,\mathcal{J}_{\mathcal{D}_j},\ldots\right]}\prod_{c=1}^{2}\left(\prod_{\mathcal{D}_j\in\Gamma_c}\mathcal{U}_{\mathcal{D}_j}(\cdot)\right)$$
$$\text{s.t., }\Gamma_1=\mathbb{Q}_{\mathcal{W}_i},\Gamma_2=\mathbb{B}_{\mathcal{W}_i}\text{ and }\mathcal{U}_{\mathcal{D}_j}(\cdot)=\begin{cases}\mathcal{U}_{\mathcal{D}_j}^{QPS}(\cdot), & \text{if } \mathcal{D}_j\in\Gamma_1\\ \mathcal{U}_{\mathcal{D}_j}^{BES}(\cdot), & \text{if}\mathcal{D}_j\in\Gamma_2\end{cases} \tag{11}$$

3.4 Main steps of our LTE/WiFi spectrum allocation algorithm

In this study, we propose a new spectrum allocation algorithm to characterize the LTE/WiFi system platform. To reach the best fair-efficient solution, we adopt the concepts of cooperative bargaining games, and implement the *NBS*, *PNBS* and *ZGBS*. For the negotiation between the $\mathfrak{B}$ and $\mathcal{W}_i$, the $\mathbb{G}_{\mathcal{W}}^{\mathfrak{B}}$, $\mathbb{G}_{\mathfrak{B}}$ and $\mathbb{G}_{\mathcal{W}_i}$ games are developed for *BESs* and

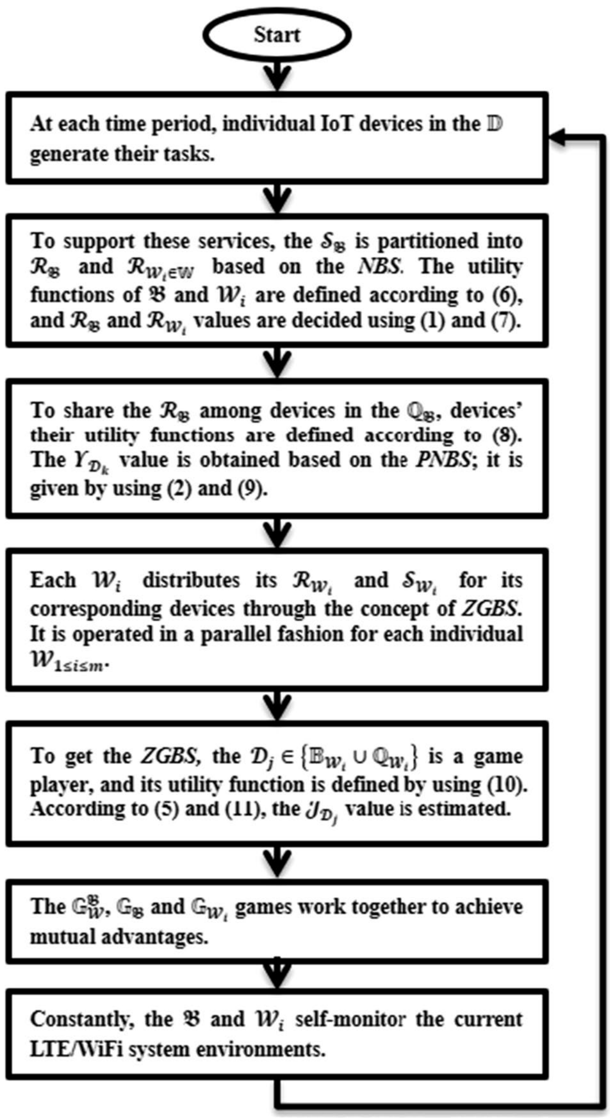

Fig. 2 Flowchart of proposed algorithm

QPSs. During discrete time periods, these games are operated repeatedly in a step-by-step online manner. Owing to the desirable characteristics of *NBS*, *PNBS* and *ZGBS*, the $\mathcal{S}_{\mathfrak{B}}$ and $\mathcal{S}_{\mathcal{W}_i}$ can be effectively shared under dynamic LTE/WiFi network environments. In the proposed scheme, we do not focus on trying to get an optimal solution based on the traditional optimal approach. Instead, the decision mechanism in our interactive bargaining model is implemented with a polynomial complexity. The main steps of our proposed algorithm can be described as follows, and they are described by Fig. 2:

Step 1: The values of control parameters are listed in Table 2, and the simulation testbed is given in Sect. 4.
Step 2: At each time epoch, multiple devices in the coverage region of the LAA-LTE macro-cell generate their communication tasks. To support these services, the $\mathfrak{B}$ and $\mathcal{W}_{1\leq i\leq m}$ negotiate with each other in the step-by-step interactive and parallel fashion.
Step 3: At the first phase, the $\mathbb{G}_{\mathcal{W}}^{\mathfrak{B}}$ is designed to partition the $\mathcal{S}_{\mathfrak{B}}$ into $\mathcal{R}_{\mathfrak{B}}$ and $\mathcal{R}_{\mathcal{W}_{1\leq i\leq m}}$, which are allocated $\mathfrak{B}$ and $\mathcal{W}_i$, respectively. For this partitioning problem, the *NBS* is adopted.
Step 4: In the $\mathbb{G}_{\mathcal{W}}^{\mathfrak{B}}$ game, utility functions of $\mathfrak{B}$ and $\mathcal{W}_i$ are defined according to (6), and $\mathcal{R}_{\mathfrak{B}}$ and $\mathcal{R}_{\mathcal{W}_i}$ are decided using (1) and (7).
Step 5: At the second phase, the $\mathbb{G}_{\mathfrak{B}}$ game is implemented to share the $\mathcal{R}_{\mathfrak{B}}$ among devices in the $\mathbb{Q}_{\mathfrak{B}}$. For this game, the *PNBS* is preferred for the solution of $\mathbb{G}_{\mathfrak{B}}$.
Step 6: In the $\mathbb{G}_{\mathfrak{B}}$ game, the $\mathcal{D}_k \in \mathbb{Q}_{\mathfrak{B}}$ is a game player, and its utility function is defined according to (8). By using (2) and (9), the $\Upsilon_{\mathcal{D}_k}$ value is obtained.

Table 2 System parameters used in the simulation experiments

Parameter	Value	Description
n	100	The total number of IoT devices
m	5	The total number of WiFi APs
$\mathcal{S}_{\mathfrak{B}}$	200 Gbps	Total spectrum capacity of $\mathfrak{B}$
$\mathcal{S}_{\mathcal{W}}$	40 Gbps	Total spectrum capacity of each $\mathcal{W}$
η	10	A control parameter for the $\mathfrak{U}_{\mathfrak{B}}^t(\cdot)$
β, κ, ω	0.8, 1, 3	Control parameters for the $\mathfrak{U}_{\mathcal{W}}^t(\cdot)$
ψ, ϱ	1, 1.5	Control parameters for the $U_{\mathcal{D}}^t(\cdot)$
BSU	8 Mbps	A pre-defined minimum amount for spectrum allocation
ξ, α, τ	1, 6, 3	Control parameters for the $\mathcal{U}_{\mathcal{D}}^{BES}(\cdot)$

Types	Applications	Spectrum maximum requirement ($\mathcal{T}_{\mathcal{D}}$)	Service duration
QPSs	I	80 Mbps	20 *t*
	II	32 Mbps	25 *t*
	III	16 Mbps	30 *t*
BESs	IV	64 Mbps	35 *t*
	V	24 Mbps	40 *t*
	VI	128 Mbps	15 *t*

Step 7: At the third phase, each $\mathcal{W}_i$ distributes its $\mathcal{R}_{\mathcal{W}_i}$ and $\mathcal{S}_{\mathcal{W}_i}$ for its corresponding devices through the $\mathbb{G}_{\mathcal{W}_i}$ game. It is operated in a parallel fashion for each individual $\mathcal{W}_{1\leq i\leq m}$.

Step 8: In the $\mathbb{G}_{\mathcal{W}_i}$ game, the $\mathcal{D}_j \in \left\{\mathbb{B}_{\mathcal{W}_i} \cup \mathbb{Q}_{\mathcal{W}_i}\right\}$ is a game player, and its utility function is defined by using (10). Based on the idea of *ZGBS*, the $\mathcal{J}_{\mathcal{D}_j}$ value is estimated according to (5) and (11).

Step 9: The $\mathbb{G}_{\mathcal{W}}^{\mathfrak{B}}$, $\mathbb{G}_{\mathfrak{B}}$ and $\mathbb{G}_{\mathcal{W}_i}$ games work together to achieve mutual advantages. Constantly, the $\mathfrak{B}$ and $\mathcal{W}_i$ self-monitor the current LTE/WiFi system environments. Proceed to Step 2 for the next game process.

4 Performance evaluation

This section describes how the proposed scheme is evaluated while comparing with other existing methods such as *QARA*, *LUSA* and *DFQG* protocols in [2, 12, 13]. This section comprises two subsections. The first subsection demonstrates the experimental method for the LTE/WiFi system, describes control parameter values, and explains a simulation scenario. The second subsection presents the simulation results with numerical analysis and discussion.

4.1 Experimental method

To develop our simulation model, we have used the simulation language 'MATLAB.' MATLAB's high-level syntax and dynamic types are ideal for model prototyping, and it is widely used in academic and research institutions as well as industrial enterprises. For the performance comparison, we adopt the simulation scenario and LTE/WiFi network environment setup as follows:

- The simulated LTE/WiFi system platform consists of one $\mathfrak{B}$, five $\mathcal{W}$ APs and one hundred IoT devices where $|\mathbb{W}| = 5$ and $|\mathbb{D}| = 100$.
- The $\mathcal{W}$ APs are regularly placed, and IoT devices are randomly distributed in the coverage area of LAA-LTE macro-cell.
- Total communication capacity ($\mathcal{S}_{\mathfrak{B}}$) of $\mathfrak{B}$ is 200 Gbps, and total communication capacity ($\mathcal{S}_{\mathcal{W}}$) of each individual $\mathcal{W}$ is 40 Gbps.
- The disagreement points, i.e., $d_{\mathfrak{B}}, d_{\mathcal{W}_i}, d_{\mathcal{D}_j}$, of all bargaining games are assumed as zeros.
- To reduce computation complexity, the amount of spectrum allocation process is specified in terms of basic spectrum units (BSUs), where one BSU is the minimum amount (e.g., 8 Mbps in our system) of spectrum allocation.
- Wireless communication tasks are generated in each individual IoT device. At each time epoch, the generation process for task services is Poisson with rate Λ (services/t), and the range of offered workload was varied from 0 to 3.0.
- Six different communication task services are categorized into two type services: *QPSs* and *BESs*. They are assumed based on their communication requirements, and service duration times.

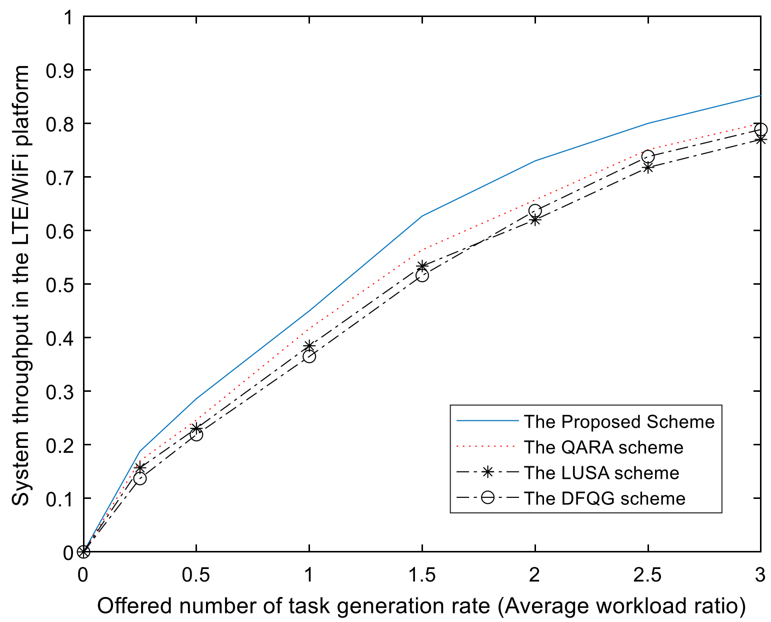

Fig. 3 LTE/WiFi system throughput. From the viewpoint of system operator, it is a key performance evaluation factor

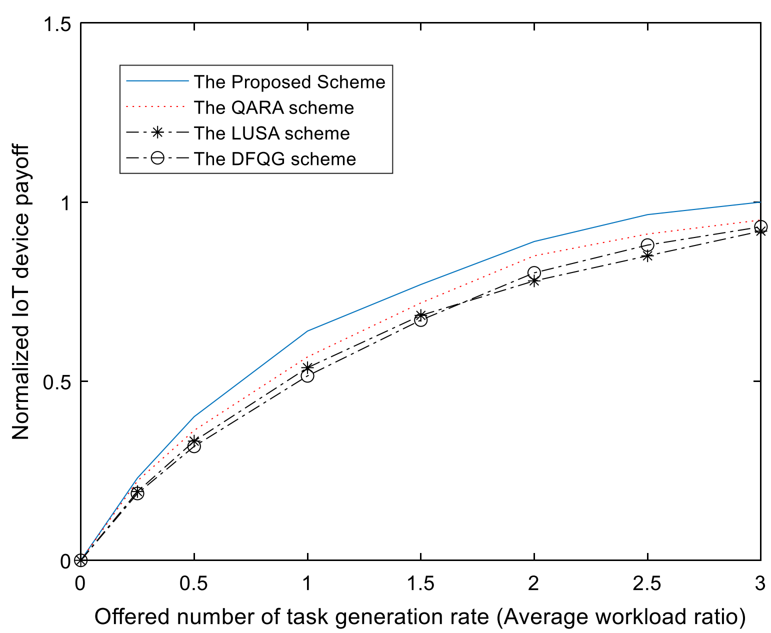

Fig. 4 Normalized IoT device payoff. The normalized IoT device payoff represents the communication resource efficiency of the LTE/WiFi system

- System performance measures obtained on the basis of 100 simulation runs are plotted as a function of the offered task request workload.

4.2 Simulation results with numerical analysis

Figure 3 depicts the variations of the LTE/WiFi system throughput, which is obtained as a function of increasing workload rate. Analyzing the data, one may notice that the system throughput grows as workload arrival rate increases. This is explained by the fact that the workload increasing makes the LTE/WiFi system more profitable by providing more communication services. From the simulation results, we can observe that the throughput of our proposed scheme is higher than that of the *QARA*, *LUSA* and *DFQG* schemes. This outcome indicates that our proposed method can dynamically allocate the limited LTE/WiFi spectrum resources to ensure the *BESs* and *QPSs*. Therefore, we can adapt the dynamics of LTE/WiFi system under widely different traffic situations.

The analysis of the normalized IoT device payoff is shown in Fig. 4. From the results, it is important to note that our proposed scheme can achieve a better device payoff compared with the existing protocols. It is because our method has two advantages: (1) sequentially negotiation to converge a mutual consensus, and (2) reciprocal agreement for different *BESs* and *QPSs*. These features make spectrum allocation decisions adaptively from low to heavy traffic workload rates while leading to a maximized device payoff. From this discussion, we can conclude that our *NBS*-, *PNBS*- and *ZGBS*-based bargaining approach provides an effective way to share the limited LTE/WiFi spectrum resources.

Figure 5 shows the fairness per each IoT device in the LTE/WiFi system. As presented in the figure, our proposed scheme can achieve the best fairness compared to the existing state-of-the-art protocols. Traditionally, cooperative game theory attempts to ensure a relevant tradeoff between efficiency and fairness in bargaining games. The major characteristic of *NBS*, *PNBS* and *ZGBS* is to provide a fair-efficient solution. The most significant point in Fig. 5 is that our bargaining approach can

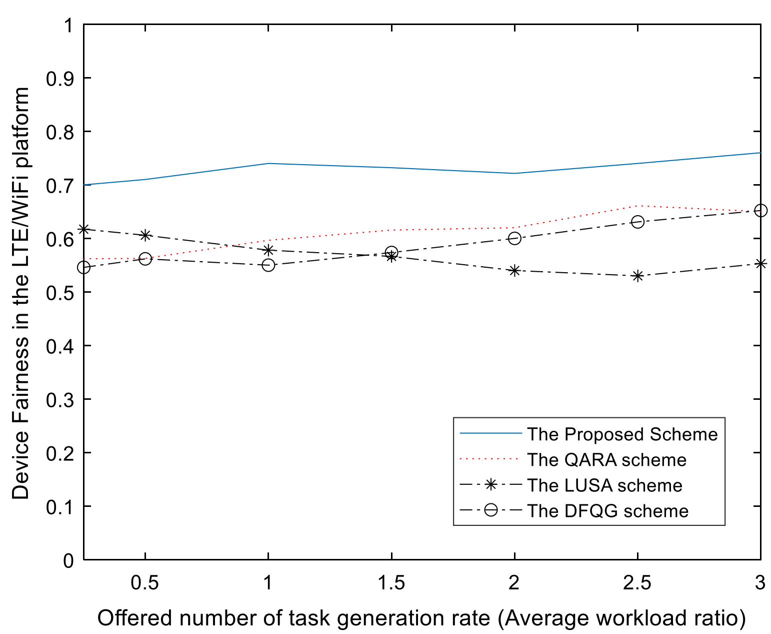

Fig. 5 Fairness per each IIoT device. It shows the fairness per each IoT device in the LTE/WiFi system

maintain the dramatically higher fairness for IoT devices for the spectrum allocation problem in the LTE/WiFi system.

Based on the above three experiments, it is obvious that the proposed scheme can strike an appropriate performance balance under widely diversified communication workload intensities in the LTE/WiFi system platform. Therefore, IoT devices in the proposed scheme take the mutual advantages through bargaining with each other. The average system throughput, payoff and fairness of IoT device are increased by 10%, 10% and 25%, respectively, in comparison with existing protocols.

5 Conclusion and future work

The LAA technology enables the coexistence of LTE and WiFi networks while potentially offering an improved network throughput. For the effective LTE/WiFi system operation, the cooperation of LTE BS onto WiFi AP can play a significant role. In this study, we investigate the LTE/WiFi system platform to design an effective spectrum allocation scheme to strike an appropriate performance balance. To tackle the LTE/WiFi spectrum allocation problem in an efficient way, the bargaining concepts are borrowed from the *NBS*, *PNBS* and *ZGBS*, and they are implemented in a step-by-step interactive fashion. In a three-phase process, our proposed bargaining model can leverage a mutual consensus to provide a fair-efficient solution. Therefore, the LTE BS, multiple WiFi APs, and their corresponding IoT devices work together to effectively share the limited LTE/WiFi spectrum resources. Based on the iterative combination of spectrum partitioning and sharing problems, we leverage a reciprocal agreement as possible while maintaining fair QoS guarantees for multiple IoT devices. Finally, simulation results have demonstrated the effectiveness and efficiency of the proposed scheme. Through the numerical analysis, it is revealed that we can lead to an improvement of more than 10% and 20% in the achievable system throughput, device's payoff and fairness as compared to that obtained with the benchmark protocols such as the *QARA*, *LUSA* and *DFQG* schemes.

Despite the many advantages of the proposed scheme, there are still challenges and new research directions in deploying the LTE/WiFi systems. First, we will consider a multi-mode BS that operates over the high-frequency mm-wave band. Here, we aim at addressing the coexistence problem of a multi-mode BS with WiFi networks. Second, we may explore the adaptive cognitive ratio technology in varied channel conditions and multi-user situations. Another interesting issue is the movement of different IoT devices. It deserves much attention in the future study.

Abbreviations

APs	Access points
BESs	Best-effort services
BS	Base station
DFQG	Delivering Fairness and QoS Guarantee
LAA	Licensed-assisted access
LBTF	Listen-before-talk functionality
LTE	Long-term evolution
LUSA	Licensed and Unlicensed Spectrum Aggregation
PNBS	Proportional Nash bargaining solution
QARA	QoS-Aware Resource Allocation
QoS	Quality of service
QPSs	QoS-preferred services
ZGBS	Zhang's group bargaining solution

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Declarations

Competing interests
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