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A New Bargaining Game-Based Unlicensed Spectrum Sharing Scheme for TVWS Platform

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ABSTRACT The rapid boosting in the Internet-of-Things (IoT) paradigm and the scarcity of available spectrum resources have hindered the improvement of capacity in 5G wireless network systems. Therefore, it is necessary to discover an appropriate spectrum sharing technology by exploiting unlicensed spectrum bands. In this study, we design a new unlicensed spectrum sharing algorithm in the television white space (TVWS) platform. According to the cooperative bargaining game theory, our proposed algorithm explores the mutual benefits to achieve a reciprocal consensus for different data application services. In a sequentially iterative manner, our game based approach adaptively makes control decisions for the TVWS spectrum sharing problem. Based on the novel bargaining solution and well-known rationing rules, we compromise the conflicting views of IoT devices while leveraging a cooperative agreement for their services. Finally, numerical simulation results show that our proposed algorithm provides a very effective tradeoff between the spectrum efficiency and service fairness compared with the existing TVWS spectrum sharing protocols.

INDEX TERMS TV white space platform, spectrum commons, spectrum sharing model, bargaining game theory, reference integrative bargaining situation.

I. INTRODUCTION

With the explosive growth of heterogeneous wireless-capable Internet of Things (IoT) devices and rapid and continuous increase in data traffic volumes in wireless networks, spectrum sharing techniques are essential for high-throughput wireless Internet access. Spectrum sharing techniques need to be carefully designed to enable inter-technology coexistence in different network systems. In recent years, policymakers, academics, and industry participants have been debating to devise new and more flexible spectrum access strategies to improve the current spectrum usage [1]. To satisfy this goal, many commentators and scholars have advocated a new concept, called *spectrum commons*; equal spectrum access rights for all users, operators and technologies. Proponents of *spectrum commons* strongly claim that new spectrum sharing technologies allow a virtually unlimited number of users to exploit the same spectrum resource without causing each other interferences [2].

From the regulatory and economical perspectives, spectrum can be broadly classified into licensed spectrum and unlicensed spectrum. Licensed spectrum is typically associated with exclusive spectrum access, but it is fairly limited and extremely expensive. Based on the given access priority to primary holders, the design of licensed spectrum sharing mechanisms is constrained. The unlicensed spectrum is a prominent example of the *spectrum commons*, which refers only to equal spectrum access rights. To facilitate the coexistence of multiple IoT devices in dense deployments, one of the most challenging issues is how to design a novel spectrum sharing mechanism for the unlicensed spectrum. It helps to put the spectrum resource to its most valuable use without waiting for a regulator's permission [1], [3].

In telecommunications, white spaces refer to the spectrum bands allocated to broadcasting services but not used locally. Regulators assign white spaces bands for specific uses and, in most cases, license the rights to broadcast over these spectrum bands. Despite the rapidly developing technologies for spectrum sharing, the assigned licensed white spaces bands are not efficiently utilized at certain times and locations.

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Recently, the Federal Communications Commission (FCC) has allowed for opportunistic access to the unused spectrum in the TV white space, i.e., TVWS, if unlicensed users assure causing no interference to the incumbents. Therefore, the opportunistic access to TVWS spectrum resource can provide a better communication capacity while improving the spectrum utilization. Based on the ongoing standardization efforts in utilizing TVWS spectrum, the coexistence of heterogeneous IoT devices in TVWS is emerging as an important research area [4]–[6].

The TVWS technology is confronted with control issues which address the dynamic spectrum sharing methods among different requirements. Until a recent date, technical progress has been made by using a spectrum database that is administrated by a database operator (DO) - appointed by the spectrum regulator to oversee the TVWS business model [6]. The DO has an authority to distribute the available TVWS spectrum bands to multiple IoT devices based on a hybrid control and service plan. It is assumed that each IoT device is equipped with a single antenna that can be tuned to a subset of TVWS spectrum bands, and individual devices make instant queries to temporarily use the available spectrum resource for heterogeneous services [6]. Each individual device can choose a set of available spectrum bands, which are not necessarily contiguous, by implementing spectrum bonding and aggregation techniques [5]–[7].

Traditionally, wireless communications combine two separate domains of applications: real-time data (class I) and non real-time data (class II) applications. Class I applications respond to external events within a bounded interval of time such as medical, fire detector, and online signal processing applications; they require a guarantee that all processing is completed within a given time constraint. Therefore, timeliness is a primary measure of correctness and a late response may result in catastrophic consequences. Whereas class II data applications, e.g., file transfer, electronic mail, and remote terminal applications, have a less rigorous notion of temporal correctness; the response time is very subjective and seldom specified such as usual best effort services. Therefore, they strive for good average-case performance and tolerate occasional slow response times [9].

To effectively share the TVWS spectrum bands with different service requests, we should formulate a TVWS spectrum management problem with respect to widely diversified communication situations. To solve this problem, one of the key challenges is to understand the behaviors of self-regarding IoT devices while adaptively mediating conflicting control issues. However, it is a complex and challenging work. Therefore, we need a new control paradigm. Game theory is a natural framework to address the conflicts between such self-interested game players. Technically, each IoT device is assumed to be a rational selfish agent. According to his local goal and information, a self-organizing agent makes control decisions to achieve his individual objective. To guide these selfish agents to achieve a globally desirable system performance, game theory is an effective tool with some attractive features [8].

A. TECHNICAL CONCEPTS

In the game theory, bargaining games are games with competition between groups of players due to the possibility of external enforcement of cooperative behavior. The main idea of bargaining game theory was initiated by Nash's seminal paper of 1950. It is a mathematical discipline which studies the problem of bargaining between two or more game players by studying the mathematical properties of maps assigning an outcome to each bargaining game [8].

Recently, there has been an increased interest in the experimental investigation of reference point effects in bargaining problems [10]. The *reference integrative bargaining situation* (*RIBS*) is one of the first studies which incorporated the notion of a reference point into the simple bargaining model. In the *RIBS*, the reference point outcome has a potential to influence the negotiated agreement especially if it is found fair by all game players. In that case, the reference point can serve as a starting point for negotiations. It is important to note that the reference point outcome does not replace the conflict outcome because each player can still veto any agreement, forcing the players to obtain their conflict payoffs. Instead, the reference point outcome is an additional important factor in determining the final outcome [10], [11].

B. MAIN CONTRIBUTIONS

According to the *RIBS*, we design a new dual bargaining model to effectively solve the spectrum sharing problem in the TVWS platform. By considering the different type applications, we design an inter-bargaining game model to divide the available unlicensed TVWS spectrum for class I and class II data services. And then, two different intra-bargaining game models are developed to share the allocated spectrum by multiple IoT devices. For the dual bargaining process, the concept of *RIBS* is adopted, but reference points are differently decided based on service characteristics. According to the step-by-step interactive and repeated bargaining process, our proposed approach leads to an appropriate performance balance in the TVWS system while effectively sharing the unlicensed spectrum resource. In detail, the major contributions of this study are summarized as;

- We investigate the idea of *RIBS* to design our TVWS spectrum sharing scheme. By considering the features of different service types, we formulate the inter and intra-bargaining games to reveal the mutual-interactive relationship among IoT devices.
- The inter-bargaining process is designed to divide the available unlicensed TVWS spectrum for class I and class II data services. To get a globally desirable solution, the concept of *RIBS* is adopted and the reference point is dynamically determined based on the rationing rule with features of service types.

- To share the allocated spectrum from the inter-bargaining process, two intra-bargaining processes are implemented to leverage a mutual advantage agreement. The idea of*RIBS* is also adopted, but the decisions of reference points are dynamically adjusted by considering the current traffic situation.
- We evaluate the performance of the proposed scheme and compare it with the other existing state-of-the-art protocols through the simulation analysis. Numerical results verify our proposed approach while offering synergistic features under dynamic changing TVWS environments.

C. ORGANIZATION

The remainder of the article is organized as follows. Section II introduces the related work. In Section III, we briefly describe the TVWS infrastructure and the spectrum sharing problem. And then, we introduce the background knowledge of *RIBS* to design our TVWS spectrum sharing scheme. Especially, we explain in detail our new bargaining game model and provide the main steps of our proposed algorithm to increase readability. Performance results and numerical analysis of our solution are presented in Section IV. It shows the advantages of our proposed scheme by comparing the existing protocols. Finally, Section V offers concluding remarks.

II. RELATED WORK

Spectrum sharing has always been an issue, however it become a more serious problem with the unlicensed spectrum bands in TVWS. In this section, we present a brief survey on recent TVWS spectrum sharing protocols. Each research work proposes unique algorithm while analyzing the system performance from different viewpoints. The paper [14] proposes a novel method that allows LTE-U and Wi-Fi networks to coexist in the same unlicensed spectrum for 5G networks. By considering coexistence issue, a game-theoretic approach is adopted to solve the multi-player interaction in this spectrum space. A virtual coalition formation game is used to solve the unlicensed band selection problem. The outcome of this game defines the optimization problem within each coalition. This optimization problem is then decomposed into two sub-problems: i) time-sharing problem between the LTE-U and Wi-Fi systems and ii) a resource allocation problem for the LTE-U system. The cooperative Kalai–Smorodinsky bargaining solution is used for solving the first sub-problem, whereas the Q-learning algorithm is used for solving the second. Simulation results show the advantages of the proposed approach in terms of percentage of unsatisfied users and fairness [14].

In [15], S. Abedin et al formulate a fog load balancing problem considering the communication and computation constraints, where the objective is to minimize the load balancing cost of the fog computing network empowered with the narrow-band IoT (NB-IoT). First, they model the time resource scheduling problem in NB-IoT as a bankruptcy game. Within the game framework, they enforce the Shapley value-based strategic policy for the NB-IoT devices to perform uplink scheduling, and also they propose greedy iterative time scheduling, complementary to the Shapley value-based scheduling but with less computational complexity. And then, they decompose the fog load balancing problem into a Hitchcock–Koopmans transportation problem that defines the over-utilized and under-utilized fog computing nodes based on the computational resource utilization. The simulation results illustrate that the average job load balancing cost with their approach is significantly reduced compared with the baseline methods [15].

In [16], S. Kim designs a new spectrum allocation scheme to effectively use the limited heterogeneous network (HetNet) spectrum resource. By employing the main ideas of relative utilitarian, equality averse and inequality averse bargaining solutions, his approach unfolds into three stages of spectrum allocation process while balancing the efficiency and fairness. Based on the main features of each bargaining solution, he hierarchically applies these three solutions to spectrum assignment among different network agents [16].

In [4], B. Bahrak and J. Park propose the *Coexistence Decision for Spectrum Sharing* (*CDSS*) scheme to access the TVWS spectrum opportunistically. This scheme is a spectrum allocation algorithm, and addresses some of the challenges about the heterogeneous wireless network coexistence. With a centralized topology, the *CDSS* scheme considers many factors in sharing the TVWS bands between different networks. This approach uses a set of constraints to formulate the decision making problem as a multi-objective combinatorial optimization problem; each of the constraints corresponds to an important prerequisite for the coexistence of heterogeneous wireless networks. By including all of the critical constraints, the *CDSS* scheme finds a Pareto optimal feasible solution. Numerical results confirm the *CDSS* scheme's effectiveness in terms of fairness and percentage of demand serviced [4].

The *Hierarchical Game based Spectrum Sharing*(*HGSS*) scheme considers a hierarchical model for the spectrum sharing in TVWS that includes a wide range of fixed and portable devices [5]. The fixed devices are allowed to share access to the unlicensed spectrum with some mobile devices in their proximity in exchange for cooperative relaying. This method can significantly improve the quality of service (QoS) for IoT devices if the quality of the direct transmission link is poor. The TV spectrum regulator can lease a part of their spectrum bands to local devices with fixed devices, and these fixed devices can decide to sublease a portion of their spectrum access time to the users with portable devices. The *HGSS* scheme is formulated as a reputation-based Stackelberg game theoretic model. This hierarchical game approach can support the coexistence of a wide range of secondary services that enforces a faithful behavior to the unlicensed users. Numerical results show that the *HGSS* scheme can improve the device's utility under different network conditions [5].

The paper [6] studies the distributed spectrum sharing problem in the opportunistic TVWS environment by using a game theoretical approach, and proposes the *Distributed Management for Spectrum Sharing*(*DMSS*) scheme. This scheme formulates the distributed TVWS spectrum management problem based on the two non-cooperative spectrum management games. In the first game, IoT devices can choose a set of non-contiguous idle spectrum bands while satisfying some hardware constraints. In the second game, IoT devices can only choose contiguous spectrum bands. In both games, IoT devices are game players, who attempts to optimize its objective function; this function provides a tradeoff between the achieved rate and cost factors. According to the best response strategy, the TVWS spectrum bands are shared by all players. The *DMSS* scheme is shown to converge in a few iterations to a pure-strategy Nash equilibrium. In addition, another effective algorithm is developed based on the *Imitation dynamics*. In this algorithm, a game player probabilistically imitates successful selection strategies of other players in order to improve his objective function. Based on the numerical simulation, it is demonstrated that the *DMSS* scheme provides a very effective system performance [6].

Until now, some existing protocols [4]–[6], [14]–[16] have proposed novel ideas for the spectrum sharing problems. Protocols in papers [5], [6], [14]–[16] are designed based on game theory, and schemes in papers [4]–[6] are implemented for the TVWS spectrum sharing problem. Especially, the research in [16] adopts the concept of three-phase bargaining game approach to solve the spectrum sharing problem from a coordinated perspective. However, none of research literatures consider the inter and intra-bargaining approach to share the limited spectrum resource in the TVWS platform. Due to the desirable characteristics of cooperative game theory, our proposed dual bargaining game model can get a globally desirable system performance for the TVWS spectrum sharing problem.

III. THE PROPOSED TVWS SPECTRUM SHARING SCHEME

A. TVWS PLATFORM AND BARGAINING GAME MODEL

In this study, we consider a simple TVWS network cell consisting of one DO (Γ_{DO}) and n IoT devices $\mathbb{N} = \{\mathcal{D}_1, \ldots, \mathcal{D}_n\}$, which are located within the transmission range of Γ_{DO}. This platform setting can be easily extended recursively. Therefore, in a parallel manner, our one Γ_{DO} TVWS platform could be expanded into the larger-magnitude TVWS platform with multiple DOs. Each IoT device is equipped with a single antenna to communicate with the Γ_{DO}. As a central coordinator, the Γ_{DO} is responsible for assigning the unlicensed spectrum resource to devices in $\mathbb{N}$. To be specific, regulators such as FCC prescribe rules and mechanisms for protecting licensed devices operating in TV bands, but no such rules exist for unlicensed devices. To fill this void, the Γ_{DO} makes control decisions in order to solve the unlicensed spectrum sharing problem. The overview of TVWS system platform is shown in Fig.1 [4],[7].

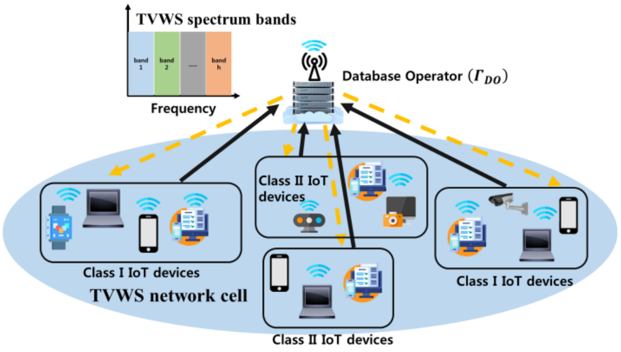


FIGURE 1. **Overview of TVWS system platform.**

Let $\mathfrak{M}$ denote the potentially available unlicensed spectrum; it is the set of idle TVWS spectrum bands. B is the spectrum band size, and it is same for all bands. Given the spectrum status, individual bands, which are not necessarily contiguous, can be aggregated [6]. This feature is used to take into account the channel bonding technology. Usually, the dynamic spectrum sharing problem is formulated based on spectrum needs and its availability; it must address some of the challenges to handle the coexistence situation of heterogeneous IoT devices while considering many factors in different type services [6]. It falls into the category of bargaining games because the goal of all rational and independent devices is to reach a mutually acceptable consensus. In this study, we choose the concept of bargaining game to develop a new TVWS spectrum sharing scheme. Based on our bargaining approach, we can guide individual devices to achieve a globally desirable TVWS system performance.

In the proposed scheme, we divide the operating time of the system into discrete time epochs, and in each time epoch, the available TVWS spectrum is shared among IoT devices based on the bargaining game ($\mathbb{G}$). To support different types of application services, the $\mathbb{G}$ consists of one inter-bargaining game ($\mathcal{G}$) and two intra-bargaining games ($G_I \text{and} G_{II}$). In the $\mathcal{G}$, class I and class II service types are game players, and the available TVWS spectrum amount at time epoch t ($\mathfrak{M}_t$) is shared by them. As the interim results of the $\mathcal{G}$, $\mathfrak{M}_t^I$ and $\mathfrak{M}_t^{II}$ are obtained; $\mathfrak{M}_t^I (or \mathfrak{M}_t^{II})$ is allocated for class I (*or* class II) application services where $\mathfrak{M}_t = \mathfrak{M}_t^I + \mathfrak{M}_t^{II}$. In the $G_I (or G_{II})$, IoT devices with class I (*or* class II) applications are game players, and the $\mathfrak{M}_t^I (or \mathfrak{M}_t^{II})$ is re-distributed to players. Our inter and intra-bargaining games are operated interactively, and two intra-games, i.e., G_I and G_{II}, are operated in a distributed parallel fashion. At each epoch, the $\mathbb{G}$ is repeated sequentially during the step-by-step iteration, and the $\mathfrak{M}$ is adaptively shared based on the idea of bargaining solution. Formally, we define the $\mathbb{G}$ game entities, i.e,

$$\begin{aligned}
\mathbb{G} &= \{\mathcal{G}, (G_I, G_{II})\} \\
&= \left\{\Gamma_{DO}, \mathbb{N}, \ \mathfrak{M}, \left\{\mathcal{G} | \left(\mathcal{P}_I, \mathcal{P}_{II}\right), \mathbb{S}_{\mathcal{G}}, (U_I, U_{II})\right\}, \right. \\
&\qquad \left. \left\{G_I | \mathcal{D}_i \in \mathbb{N}_I, \mathbb{S}_{G_I}, \mathfrak{U}_{\mathcal{D}_i}^I\right\}, \left\{G_{II} | \mathcal{D}_j \in \mathbb{N}_{II}, \mathbb{S}_{G_{II}}, \mathfrak{U}_{\mathcal{D}_j}^{II}\right\}, T\right\}
\end{aligned}$$

- In the $\mathbb{G}$, $\mathcal{G}$ and G_I, G_{II} games are mutual and reciprocal interdependent in an interactive manner, and they work together to share the available TVWS spectrum ($\mathfrak{M}$).
- Γ_{DO} is the DO of TVWS platform, and it is a coordinator for the spectrum sharing process.
- $\mathbb{N}$ is the set of IoT devices, i.e., $\mathcal{D}_{1\leq i\leq n}$, which are unlicensed secondary users to share the $\mathfrak{M}$.
- In the $\mathcal{G}$, the group of class I (*or* class II) applications are $\mathcal{P}_I(or\ \mathcal{P}_{II})$, and they are game players. The utility function of $\mathcal{P}_I(or\ \mathcal{P}_{II})$ is $U_I(or U_{II})$, and $\mathbb{S}_{\mathcal{G}}$ is their strategy set for the spectrum sharing problem.
- $\mathbb{N}_I$ is the set of IoT devices, which constantly generate the class I application services. Devices in $\mathbb{N}_I$ are game players in the G_I. For each player, $\mathfrak{U}_D^I$ is a utility function and $\mathbb{S}_{G_I}$ is his strategy set.
- $\mathbb{N}_{II}$ is the set of IoT devices, which constantly generate the class II application services. Devices in $\mathbb{N}_{II}$ are game players in the G_{II}. For each player, $\mathfrak{U}_D^{II}$ is a utility function and $\mathbb{S}_{G_{II}}$ is his strategy set.
- Discrete time model is represented by a sequence of time steps. Each time step, i.e., $t_c \in T = \{t_1, \ldots, t_c, t_{c+1}, \ldots\}$, matches the $\mathbb{G}$'s event time-scale.

B. THE BASIC CONCEPTS AND AXIOMS OF RIBS

In this section, we introduce the idea of *RIBS* employed in this study. While doing this, we follow the commonly used notations for reader friendliness. $\mathbb{R}_+^n$ is the $n-$fold Cartesian product of all non-negative real number set $\mathbb{R}$. For the n game players, they need to agree on a payoff vector from a set of potential possibilities, $S\subseteq\mathbb{R}_+^n$. The feasible set (S) consists of all the utility vectors that can be achieved by game players. The disagreement point $d \in S$ represents the utility levels obtained by players if no agreement is reached. A bargaining problem is a pair (S, d) such that there exists $x \in S$ with $x \gg d$. For x, $y \in \mathbb{R}_+^n$, the vector inequalities are given as: $x \geq y$, $x > y$ and $x \gg y$. $x \geq y$ means $y_i \geq x_i$ for $i = 1, \ldots, n$; $y > x$ means $y \geq x$ and $y \neq x$; $x \gg y$ means $y_i > x_i$. For every $S \subset \mathbb{R}_+^n$, its *weakly Pareto optimal* (***WPO***) set is defined as $\boldsymbol{WPO}(S) = \{y \in S | x \gg y \text{ implies } x \notin S\}$. The *RIBS* adds a reference point to the characteristics of the bargaining situation. It is a point in S, and *Pareto* superior to d. A bargaining problem with a reference point is a triple (S, d, r) where the reference point $r \in S \backslash \boldsymbol{WPO}(S)$ satisfies $r \geq d$ [10], [11];

In the *RIBS*, another salient point, called the ideal point $\mathcal{I}(S, d) \notin S$, is employed. Originally, it was introduced by Kalai and Smorodinsky to represent an outcome in which each player is awarded the maximum utility he can hope to achieve, assuming that the other players will never accept outcomes which are worse for them than the conflict outcome [10]. Usually, ideal point is infeasible in the bargaining problem. Let $\sum^n$ be the family of all $n-$player bargaining problems with the r. The *RIBS* on $\sum^n$ is a function that associates with each triple $(S, d, r) \in \sum^n$ a unique outcome $RIBS\ (S, d, r) \in S$. Mathematically, it can be formally defined as follows [10], [11];

$$\begin{aligned} &RIBS\ (S, d, r) \\ &= \left(\left(1-\lambda^*\right) \times r\right) + \left(\lambda^* \times \mathcal{I}\left(S, d\right)\right) \\ &\quad \text{s.t., } \lambda^* \\ &= \mathbf{max}\left\{\lambda \in [0,\ 1] \,|\, \left[\left(\left(1-\lambda\right) \times r\right) + \left(\lambda \times \mathcal{I}\left(S, d\right)\right)\right] \in S\right\} \end{aligned} \tag{1}$$

Technically, the *RIBS* provides the maximum point of the feasible set on the line segment connecting the $\mathcal{I}(S, d)$ point and the r point. Therefore, it is the intersection point of the *Pareto* frontier of S and that line segment [10]. This is equivalent to saying that the *RIBS* selects the maximum individually rational payoff profile at which each player's payoff gain from his reference point has the same proportion to the payoff difference between his ideal point and his reference point. Consequentially, the disagreement point d does not have a direct influence to get the *RIBS*. However, it has an indirect influence on the bargaining process as it is used to derive the ideal point. Figure 2 provides a graphical illustration of the *RIBS* for a two-player bargaining game [10], [11].

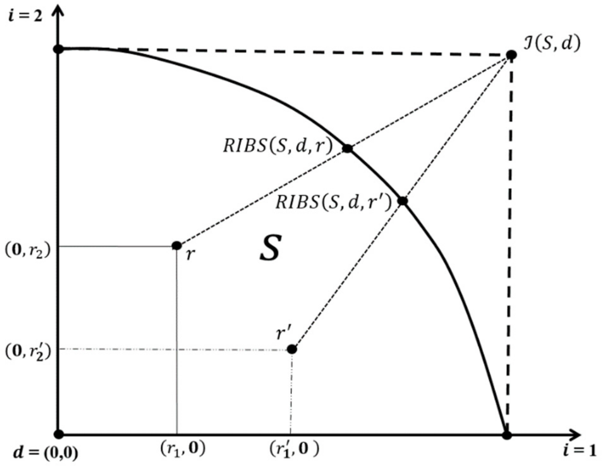


FIGURE 2. The idea of ***RIBS*** with two different references.

The *RIBS* is characterized by a collection of desirable axioms like as, *weakly Pareto optimal* (***WPO***), *relevant domain* (***RD***), *symmetry* (***S***), *restricted monotonicity* (***RM***), *limited sensitivity to changes in the conflict point* (***LSCCP***) and *Invariance under Positive Linear Transformations* (***IPLT***). To explain these axioms, a solution function is any function $f: \sum^n \rightarrow \mathbb{R}_+^n$ satisfying $f(S, d, r) \in S$ for every $(S, d, r) \in \sum^n$, and the $f(S, d, r)$ is a solution point of the bargaining process [12].

- *WPO:* For every $(S, d, r) \in \Omega, f\ (S, d, r) \in WP(S)$.
- *RD:* For every bargaining domain S and a point $y \in S$, denote the set $\{x | x \in S, x \geq y\}$ by $S\,[y]$. For every $(S, d, r) \in \Omega, f\ (S, d, r) \in f\ (S\,[d]\,, d, r)$.
- *S:* For every $(S, d, r) \in \sum^n$, if (S, d, r) is symmetric, then $f_1\ (S, d, r) = f_2\ (S, d, r)$.

- *RM:* For every pair (S, d, r), $(S', d, r) \in \sum^{n}$, if $S' \subseteq S$, $S \backslash S' \subseteq S[d]$ and $\mathcal{I}(S', d) = \mathcal{I}(S, d)$, then $f(S', d, r) \leq f(S, d, r)$.
- *LSCCP:* For every pair (S, d, r), $(S, d', r) \in \sum^{n}$, if $\mathcal{I}(S, d') = \mathcal{I}(S, d)$, then $f(S, d', r) \in f(S, d, r)$.
- *IPLT:* Let $\mathcal{T}$ be a positive linear transformation. For every $(S, d, r) \in \Omega, f(\mathcal{T}S, \mathcal{T}d, \mathcal{T}r) \in \mathcal{T}f(S, d, r)$.

C. THE INTER AND INTRA BARGAINING GAMES IN THE TVWS PLATFORM

At time $t_c \in T$, IoT devices generate independently their service requests. To support these requests, the Γ_{DO} adaptively allocates the currently available $\mathfrak{M}_{t_c}$ to devices while considering different QoS requirements. At the first step, the $\mathcal{G}$ game is started to divide the $\mathfrak{M}_{t_c}$ into two parts; $\mathfrak{M}^{I}_{t_c}$ is for the $\mathcal{P}_I$, and $\mathfrak{M}^{II}_{t_c}$ is for the $\mathcal{P}_{II}$. In the $\mathcal{G}$, the utility functions of $\mathcal{P}_I$ and $\mathcal{P}_{II}$ at time t_c $(U_I(\cdot) \text{ and} U_{II}(\cdot))$ are formally defined as follows;

$$\begin{cases} U_I\left(t_c, \mathfrak{M}^{I}_{t_c}, \mathcal{Q}^{I}_{t_c}\right) = \left(\eta \times \left(\theta + \frac{\alpha}{\Gamma}\right)^{\Gamma}\right) - \phi \\ U_{II}\left(t_c, \mathfrak{M}^{II}_{t_c}, \mathcal{Q}^{II}_{t_c}\right) \\ = \gamma \times \log\left(\xi - \frac{(\mathbf{min}(\mathfrak{M}^{II}_{t_c}, \mathcal{Q}^{II}_{t_c})/\mathcal{Q}^{II}_{t_c})}{\psi}\right) \end{cases}$$
$$\text{s.t., } \Gamma = \frac{\mathbf{min}\left(\mathfrak{M}^{I}_{t_c}, \mathcal{Q}^{I}_{t_c}\right)}{\mathcal{Q}^{I}_{t_c}} \text{and} \left(\mathfrak{M}^{I}_{t_c} + \mathfrak{M}^{II}_{t_c}\right) \leq \mathfrak{M}_{t_c} \quad (2)$$

where $\mathfrak{M}^{I}_{t_c}, \mathcal{Q}^{I}_{t_c}$ $\left(or\ \mathfrak{M}^{II}_{t_c}, \mathcal{Q}^{II}_{t_c}\right)$ are the allocated and requested spectrum resources for the $\mathcal{P}_I$ $(or\ \mathcal{P}_{II})$, respectively. η, θ, α and ϕ are adjustment parameters for the $U_I(\cdot)$, and γ, ξ and ψ are control factors for the $U_{II}(\cdot)$. To adaptively adjust the $\mathfrak{M}^{I}_{t_c}$ and $\mathfrak{M}^{II}_{t_c}$ values at time t_c, we use the idea of *RIBS*. Therefore, we should decide the reference point $\left(r^{\mathcal{G}}_{t_c}\right)$ for the $\mathcal{G}$ game. To adapt the current TVWS traffic conditions, we assume the $r^{\mathcal{G}}_{t_c}$ decision problem as a standard rationing problem. Traditionally, a rationing problem is formulated as follows. $\mathcal{R}$ is the resource, and $\mathbb{C} = \{\ldots \mathbb{C}_i \ldots\} \in \mathbb{R}^{|\mathbb{C}|}_{+}$ be the claims of creditors where $|\mathbb{C}|$ is the cardinality of $\mathbb{C}$ and $0 \leq \mathcal{R} < \sum_{i=1}^{i=|\mathbb{C}|} \mathbb{C}_i$. There are two well-known rules defined for standard rationing problems: the *constrained equal awards*(*CEA*) rule, and the *constrained equal losses*(*CEL*) rule. Mathematically, the *CEA* and *CEL* rules are defined as follows [13];

$$\begin{cases} CEA_i(\mathcal{R}, \mathbb{C}) = \mathbf{min}\{\mathbb{C}_i, \lambda\}, \\ \text{s.t., } 0 < \lambda \in \mathbb{R} \text{ and } \sum_{i=1}^{i=|\mathbb{C}|} \mathbf{min}\{\mathbb{C}_i, \lambda\} = \mathcal{R} \\ CEL_i(\mathcal{R}, \mathbb{C}) = \mathbf{max}\{0, (\mathbb{C}_i - \lambda)\} \\ \text{s.t., } 0 < \lambda \in \mathbb{R} \text{ and } \sum_{i=1}^{i=|\mathbb{C}|} \mathbf{max}\{0, (\mathbb{C}_i - \lambda)\} = \mathcal{R} \end{cases} \quad (3)$$

To estimate the $r^{\mathcal{G}}_{t_c}$, we should consider the relative fairness between class I and class II application services. For this inter-bargaining process, it is necessary to use exogenous information, namely *ex-ante* condition ($\mathbb{E}$). In the rationing problem, the $\mathbb{E}$ reflects each creditor's initial condition of the corresponding resource. Hence, it reveals inequalities between creditors that might suggest payoff compensations in favor of some creditors and to the detriment of others. Mathematically, the *CEA* rule with $\mathbb{E}$, i.e., *CEA*($\mathcal{R}$, $\mathbb{C}, \mathbb{E}$), is defined as follows [13];

$$\begin{aligned} & CEA_i(\mathcal{R}, \mathbb{C}, \mathbb{E}) \\ & \quad = \mathbf{min}\left\{\mathbb{C}_i, (\lambda - \mathbb{E}_i)_{+}\right\} \\ & \qquad \text{s.t., } 0 < \lambda \in \mathbb{R}, \mathbb{C}_i \in \mathbb{C}, \mathbb{E}_i \in \mathbb{E} \\ & \qquad \text{and} \sum_{i=1}^{i=|\mathbb{C}|} CEA_i(\mathcal{R}, \mathbb{C}, \mathbb{E}) = \mathcal{R} \end{aligned} \quad (4)$$

In the proposed scheme, we employ the *CEA*($\mathcal{R}$, $\mathbb{C}, \mathbb{E}$) to dynamically decide the $r^{\mathcal{G}}_{t_c}$ value. According to (4), the $r^{\mathcal{G}}_{t_c}$ is given by;

$$\begin{aligned} r^{\mathcal{G}}_{t_c} &= CEA_{\mathcal{L} \in \{\mathcal{P}_I, \mathcal{P}_{II}\}}(\mathcal{R}, \mathbb{C}, \mathbb{E}) \\ &= \mathbf{min}\left\{\mathbb{C}_{\mathcal{L}}, (\lambda - \mathbb{E}_{\mathcal{L}})_{+}\right\} \\ & \quad \text{s.t., } \begin{cases} \mathcal{R} = \frac{\mathfrak{M}_{t_c}}{\delta}, \mathbb{C} = \left(\mathbb{C}_{\mathcal{P}_I}, \mathbb{C}_{\mathcal{P}_{II}}\right) = \left(\frac{\mathcal{Q}^{\mathcal{P}_I}_{t_c}}{\delta}, \frac{\mathcal{Q}^{\mathcal{P}_{II}}_{t_c}}{\delta}\right) \\ 0 < \lambda \in \mathbb{R}, \\ \mathbb{E} = [\nu_I \times \lambda, \nu_{II} \times \lambda], \\ \sum_{\mathcal{L} \in \{\mathcal{P}_I, \mathcal{P}_{II}\}} CEA_{\mathcal{L}}(\mathcal{R}, \mathbb{C}, \mathbb{E}) = \mathcal{R} \end{cases} \end{aligned} \quad (5)$$

where $\mathcal{R}$ is the cut-down spectrum resource and δ is the modification factor in the *CEA* rule. In the $\mathbb{E}$, ν_I and ν_{II} are the compensating factors for the class I and class II data services, respectively. According to (5), the $r^{\mathcal{G}}_{t_c}$ is estimated, and the *RIBS* for the $\mathcal{G}$, i.e., $RIBS_{\mathcal{G}}(\cdot)$, is given by;

$$\begin{aligned} & RIBS_{\mathcal{G}}\left((U_I(\cdot), U_{II}(\cdot)), S_{\mathcal{G}}, r^{\mathcal{G}}_{t_c}, d_{\mathcal{G}}\right) \\ & = \underset{\lambda \in [0,\ 1]}{\mathbf{max}} \left\{(\mathcal{P}_I, \mathcal{P}_{II}) \mid \left[\left((1-\lambda) \times r^{\mathcal{G}}_{t_c}\right) + \left(\lambda \times \mathcal{I}\left(S_{\mathcal{G}}, d_{\mathcal{G}}\right)\right)\right] \right. \\ & \qquad \left. \in S_{\mathcal{G}}\right\} \\ & \qquad \text{s.t., } \mathcal{I}\left(S_{\mathcal{G}}, d_{\mathcal{G}}\right) \\ & = \underset{K \in \{I, II\}}{\mathbf{max}} \left\{U_K(\cdot) \in \mathbb{R} \mid \left(U_K(\cdot), (d_{\mathcal{G}})_{-K}\right) \in S_{\mathcal{G}}\right\} \end{aligned} \quad (6)$$

where $d_{\mathcal{G}}$ is the disagree point in the $\mathcal{G}$, and it is set to zeros. According to (6), the $\mathfrak{M}^{I}_{t_c}$ and $\mathfrak{M}^{II}_{t_c}$ values are obtained. And then, for the second step, the $\mathfrak{M}^{I}_{t_c}$ $\left(or\ \mathfrak{M}^{II}_{t_c}\right)$ is distributed for the multiple IoT devices in $\mathbb{N}_I$ $(or\ \mathbb{N}_{II})$. At the G_I, each $\mathcal{D}_i \in \mathbb{N}_I$ is a game player, and the utility function of $\mathcal{D}_i$, i.e., $\mathfrak{U}^{I}_{\mathcal{D}_i}(\cdot)$, is mathematically given as follows;

$$\begin{aligned} \mathfrak{U}^{I}_{\mathcal{D}_i \in \mathbb{N}_I}\left(t_c, \mathfrak{M}^{\mathcal{D}_i}_{t_c}, \mathcal{Q}^{\mathcal{D}_i}_{t_c}\right) &= \frac{exp(\Delta) - exp(-\Delta)}{exp(\Delta) + exp(-\Delta)} \\ \text{s.t., } \Delta &= \frac{\mathbf{min}\left(\mathfrak{M}^{\mathcal{D}_i}_{t_c}, \mathcal{Q}^{\mathcal{D}_i}_{t_c}\right)}{\mathcal{Q}^{\mathcal{D}_i}_{t_c}} \end{aligned} \quad (7)$$

where $\mathfrak{M}_{t_c}^{\mathcal{D}_i}$, $\mathcal{Q}_{t_c}^{\mathcal{D}_i}$ are the allocated and requested spectrum resources for the $\mathcal{D}_i \in \mathbb{N}_I$. To adaptively allocate the $\mathfrak{M}_{t_c}^{I}$ for devices in $\mathbb{N}_I$, we also adopt the idea of*RIBS*. Therefore, at time t_c, we need the reference point $\left(r_{t_c}^{G_I}\right)$ for the G_I game. In a similar fashion with the $r_{t_c}^{\mathcal{G}}$, the $r_{t_c}^{G_I}$ is decided based on the *CEA* rule. However, there is an equivalent priority in all game players. Therefore, the factor $\mathbb{E}$ is not necessary for this intra-bargaining process. Finally, the $r_{t_c}^{G_I}$ is given by;

$$\begin{aligned} r_{t_c}^{G_I} &= CEA_{\mathcal{D}_i \in \mathbb{N}_I}\left(\mathcal{R}^I,\ \mathbb{C}^I\right) \\ &= \mathbf{min}\left\{\mathbb{C}_{\mathcal{D}_i}^I,\ \lambda^I\right\} \\ &\quad \text{s.t.,} \begin{cases} \mathcal{R}^I = \dfrac{\mathfrak{M}_{t_c}^{\mathcal{P}_I}}{\varepsilon} \text{and } \mathbb{C}^I = \left\{\mathbb{C}_{\mathcal{D}_i \in \mathbb{N}_I}^I \middle| \dfrac{\mathcal{Q}_{t_c}^{\mathcal{D}_i}}{\varepsilon}\right\} \\ 0 < \lambda^I \in \mathbb{R} \text{ and } \displaystyle\sum_{\mathcal{D}_i \in \mathbb{N}_I} \mathbf{min}\left\{\mathbb{C}_{\mathcal{D}_i}^I,\ \lambda^I\right\} = \mathcal{R}^I \end{cases} \end{aligned} \tag{8}$$

where ε is the modification factor in the *CEA* rule. According to (8), the $r_{t_c}^{G_I}$ is obtained, and the *RIBS* for the G_I, i.e., $RIBS_{G_I}(\cdot)$ is given by;

$$\begin{aligned} &RIBS_{G_I}\left(\mathfrak{U}_{\mathcal{D}_i \in \mathbb{N}_I}^I(\cdot), S_{G_I}, r_{t_c}^{G_I}, d_{G_I}\right) \\ &\quad = \max_{\lambda \in [0,\ 1]}\left\{\mathcal{D}_i \in \mathbb{N}_I \middle| \begin{bmatrix} \left((1-\lambda) \times r_{t_c}^{G_I}\right) \\ +\left(\lambda \times \mathcal{I}\left(S_{G_I}, d_{G_I}\right)\right) \end{bmatrix} \in S_{G_I}\right\} \\ &\qquad \text{s.t., } \mathcal{I}\left(S_{G_I}, d_{G_I}\right) \\ &\quad = \max_{\mathcal{D}_i \in \mathbb{N}_I}\left\{\mathfrak{U}_{\mathcal{D}_i}^I(\cdot) \in \mathbb{R} \middle| \left(\mathfrak{U}_{\mathcal{D}_i}^I(\cdot), \left(d_{G_I}\right)_{-\mathcal{D}_i}\right) \in S_{G_I}\right\} \end{aligned} \tag{9}$$

By using (9), the $\mathfrak{M}_{t_c}^{I}$ is adaptively distributed for the $\mathcal{D}_i \in \mathbb{N}_I$. With the G_I game, the other intra-bargaining game G_{II} is operated simultaneously and independently to distribute the $\mathfrak{M}_{t_c}^{II}$ to devices in $\mathbb{N}_{II}$. At the G_{II} game, each $\mathcal{D}_j \in \mathbb{N}_{II}$ is a game player, and the utility function of $\mathcal{D}_j$, i.e., $\mathfrak{U}_{\mathcal{D}_j}^{II}(\cdot)$, is mathematically given as follows;

$$\begin{aligned} &\mathfrak{U}_{\mathcal{D}_j}^{II}\left(t_c, \mathfrak{M}_{t_c}^{\mathcal{D}_j}, \mathcal{Q}_{t_c}^{\mathcal{D}_j}\right) \\ &= \left(\frac{\mu \times \mathcal{H}}{\sigma + exp\left(\mathcal{H}\right)}\right) \times exp\left(\log\left(\mathcal{H}+\beta\right)\right) \\ &\quad \text{s.t.,} \mathcal{H} = \frac{\mathbf{min}\left(\mathfrak{M}_{t_c}^{\mathcal{D}_j}, \mathcal{Q}_{t_c}^{\mathcal{D}_j}\right)}{\mathcal{Q}_{t_c}^{\mathcal{D}_j}} \end{aligned} \tag{10}$$

where $\mathfrak{M}_{t_c}^{\mathcal{D}_j}$, $\mathcal{Q}_{t_c}^{\mathcal{D}_j}$ are the allocated and requested spectrum resources for the $\mathcal{D}_j \in \mathbb{N}_{II}$. μ, σ and β are adjustment parameters for the $\mathfrak{U}_{\mathcal{D}_j}^{II}(\cdot)$. Based on the delay tolerant characteristics of class II type data services, we should decide the reference point for the G_{II} game $\left(r_{t_c}^{G_{II}}\right)$. In the proposed scheme, the $r_{t_c}^{G_{II}}$ is given based on the *CEL* rule. Like as the G_I game model, each game player has an equivalent priority, and the factor $\mathbb{E}$ is also not necessary for this intra-bargaining process [13].

$$\begin{aligned} &r_{t_c}^{G_{II}} \\ &= CEL_{\mathcal{D}_j \in \mathbb{N}_{II}}\left(\mathcal{R}^{II},\ \mathbb{C}^{II}\right) \\ &= \mathbf{max}\left\{0, \left(\mathbb{C}_{\mathcal{D}_j}^{II} -\ \lambda^{II}\right)\right\} \\ &\qquad \text{s.t.,} \begin{cases} \mathcal{R}^{II} = \dfrac{\mathfrak{M}_{t_c}^{\mathcal{P}_{II}}}{\zeta} \text{ and } \mathbb{C}^{II} = \left\{\mathbb{C}_{\mathcal{D}_j \in \mathbb{N}_{II}}^{II} \middle| \dfrac{\mathcal{Q}_{t_c}^{\mathcal{D}_j}}{\zeta}\right\} \\ 0 < \lambda^{II} \in \mathbb{R} \text{ and } \displaystyle\sum_{\mathcal{D}_j \in \mathbb{N}_{II}} \mathbf{max}\left\{0, \left(\mathbb{C}_{\mathcal{D}_j}^{II} - \lambda^{II}\right)\right\} \\ = \mathcal{R}^{II} \end{cases} \end{aligned} \tag{11}$$

where ε is the modification factor in the *CEL* rule. According to (11), the $r_{t_c}^{G_{II}}$ is given, and the *RIBS* for the G_{II}, i.e., $RIBS_{G_{II}}(\cdot)$ is given by;

$$\begin{aligned} &RIBS_{G_{II}}\left(\mathfrak{U}_{\mathcal{D}_j \in \mathbb{N}_{II}}^{II}(\cdot), S_{G_{II}}, r_{t_c}^{G_{II}}, d_{G_{II}}\right) \\ &\quad = \max_{\lambda \in [0,\ 1]}\left\{\mathcal{D}_j \in \mathbb{N}_{II} \middle| \begin{bmatrix} \left((1-\lambda) \times r_{t_c}^{G_{II}}\right) \\ +\left(\lambda \times \mathcal{I}\left(S_{G_{II}}, d_{G_{II}}\right)\right) \end{bmatrix} \in S_{G_{II}}\right\} \\ &\qquad \text{s.t., } \mathcal{I}\left(S_{G_{II}}, d_{G_{II}}\right) \\ &\quad = \max_{\mathcal{D}_j \in \mathbb{N}_{II}}\left\{\mathfrak{U}_{\mathcal{D}_j}^{II}(\cdot) \in \mathbb{R} \middle| \left(\mathfrak{U}_{\mathcal{D}_j}^{II}(\cdot), \left(d_{G_{II}}\right)_{-j}\right) \in S_{G_{II}}\right\} \end{aligned} \tag{12}$$

D. MAIN STEPS OF PROPOSED TVWS SPECTRUM SHARING GAME MODEL

In this study, we develop a novel bargaining model to adaptively distribute the TVWS spectrum for different data services. Based on the idea of *RIBS*, multiple IoT devices can cooperate with each other for a global goal. Usually, most bargaining models employ the disagreement point to determine the outcome; it can be interpreted as the alternative which the players will arrive at in the case of no agreement. However, the *RIBS* employs the reference point to measure players' payoff gains when evaluating a proposed compromise. The reference point is interpreted as an intermediate agreement which facilitates the conflict resolution process. In the proposed model, the reference points are decided according to the *CEA* and *CEL* rules in order to reach a relative fairer rationing. Based on our bargaining game approach, we can achieve a mutually desirable solution while flexibly adapting the dynamic changing TVWS conditions. The main steps of the proposed scheme can be explained as follows, and they are described by the following flowchart:

Step 1: For the proposed algorithm, the values of adjustment parameters and control factors can be found in Table 1, and the simulation scenario is given in Section IV.

Step 2: The individual IoT devices constantly generate their service requests with different types and characteristics.

Step 3: At the time t_c, the Γ_{DO} allocates the $\mathfrak{M}_{t_c}$ into multiple IoT devices based on the inter-bargaining ($\mathcal{G}$) and intra-bargaining (G_I, G_{II}) games.

Step 4:, At the first step, the $\mathfrak{M}_{t_c}$ is divided for the class I and class II data services based on the $\mathcal{G}$ game. For each service type, utility functions are defined using (2), and the reference point is decided based on the *CEA* rule with $\mathbb{E}$; it is obtained according to (5). Finally, the *RIBS* for the $\mathcal{G}$ game is achieved by using (6).

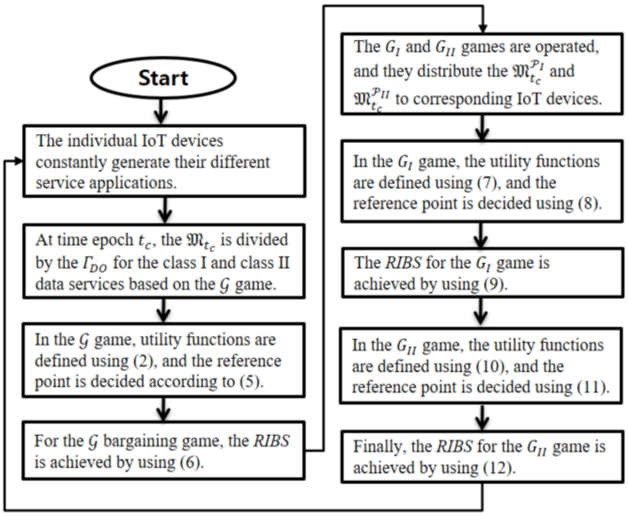
Step 5: At the second step, the G_I and G_{II} games are operated simultaneously and independently to dynamically distribute the allocated spectrum resources, i.e., $\mathfrak{M}_{t_c}^{\mathcal{P}_I}$ and $\mathfrak{M}_{t_c}^{\mathcal{P}_{II}}$ to corresponding IoT devices.

Step 6: In the intra-bargaining G_I game, the utility functions are defined using (7), and the reference point is decided based on the *CEA* rule; it is obtained according to (8). Finally, the *RIBS* for the G_I game is achieved by using (9).

Step 7: Another intra-bargaining G_{II} game, the utility functions are defined using (10), and the reference point is decided based on the *CEL* rule; it is obtained according to (11). Finally, the *RIBS* for the G_{II} game is achieved by using (12).

Step 8: During the interactive bargaining approach, heterogeneous IoT devices share the TVWS spectrum in a cooperative manner, and work together to maximize the system performance.

Step 9: Constantly, the Γ_{DO} is self-monitoring the current TVWS platform environments, and proceed to Step 2 for the next dual bargaining game process.



FLOWCHART 1. Flowchart of the proposed algorithm.

TABLE 1. System parameters used in the simulation experiments.

Parameter	Value	Description
n	10	the total number of IoT devices
B	1 Mbps	the spectrum band size
η, θ	0.9, 1	adjustment parameters for the $U_I(\cdot)$
α, ϕ	1, 0.9	adjustment parameters for the $U_I(\cdot)$
γ, ξ, ψ	-2 , 1 , 1.5	control factors for the $U_{II}(\cdot)$
μ, σ, β	1.5 , 1 , 1	adjustment parameters for the $\mathfrak{U}_{D}^{II}(\cdot)$
δ	10	the modification factor in the *CEA* rule with $\mathbb{E}$
ν_I , ν_{II}	0.1, 0.3	compensating factors for the class I and class II services
ε	10	the modification factor in the *CEA*
ζ	10	the modification factor in the *CEL* rule
n	10	the total number of IoT devices

Traffic Type	Applications	Spectrum Requirements	Service duration
Class I	1	10 Mbps (hard delay limit)	10 t
	2	15 Mbps (hard delay limit)	40 t
	3	30 Mbps (hard delay limit)	45 t
Class II	4	20 Mbps (soft delay limit)	60 t
	5	25 Mbps (soft delay limit)	90 t
	6	35 Mbps (soft delay limit)	35 t

IV. PERFORMANCE EVALUATION

In this section, we evaluate the performance of the proposed schemes by simulation. To validate the superiority of our bargaining based approach, the simulation results show the performance in terms of system throughput, device payoff and fairness, and they are compared with the existing *CDSS*, *HGSS* and *DMSS* protocols in [4]–[6]. The simulation scenario is shown as follows:

- The simulated TVWS platform consists of one Γ_{DO} and ten IoT devices where $|\mathbb{N}| = 10$.
- IoT devices are located in the covering area of Γ_{DO}; they are directly communicating with the Γ_{DO}.
- At each time epoch t, each IoT device $\mathcal{D}_{1 \leq n \leq n}$ generates its data applications for wireless communications. The generation process for data services is Poisson with rate Λ(services / t), and the range of offered services was varied from 0 to 3.0.
- The available TVWS spectrum amount at time epoch t is $\mathfrak{M}_t$; we assume the $\mathfrak{M}_t$ value to be held constant as 10 Gbps.
- The disagree point in the bargaining process is set to zeros, and each time period t is assumed as one second.
- Six different kinds of data applications are assumed based on their spectrum requirements and service duration times; they are assumed as the TVWS platform's traffic load using the unlicensed spectrum resource.
- To reduce computation complexity, the amount of spectrum allocation is specified in terms of spectrum bands, where one band size (B) is the minimum amount (e.g., 1 Mbps in our system) of allocation process.
- System performance measures obtained on the basis of 100 simulation runs are plotted as a function of the offered service request load.
- We assume the absence of physical obstacles in the wireless communications.

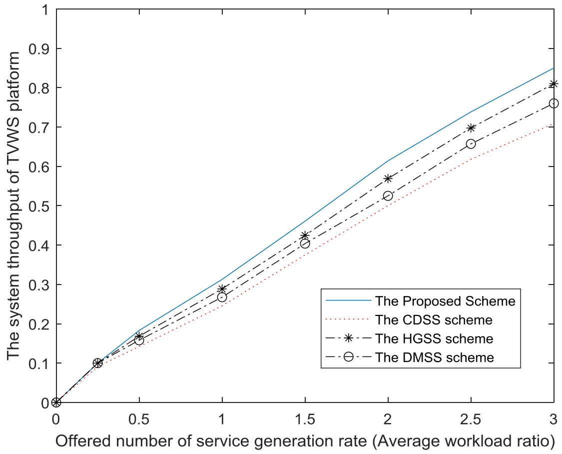


FIGURE 3. **The throughput of TVWS platform.**

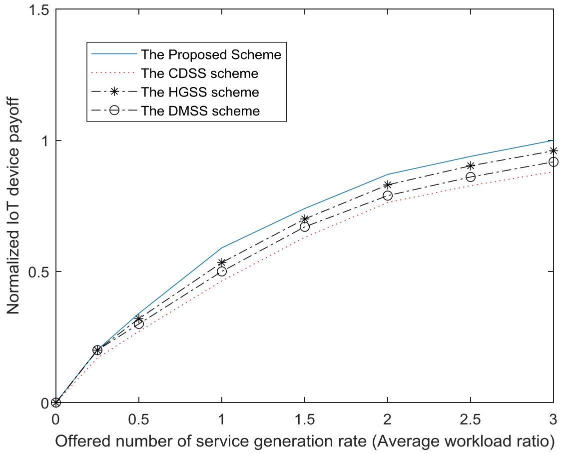


FIGURE 4. **Normalized IoT device payoff.**

Fig. 3 shows the simulation results of TVWS system throughput for various application services. The results can be explained by the fact that our bargaining based approach can provide a better system performance under widely different service load situations. It means that the *RIBS* with rationing rules can effectively handle the TVWS spectrum sharing problem while substantially increasing the overall system throughput.

In Fig.4, we investigate the evaluation results of normalized IoT device payoff. It is worth reiterating that one of our bargaining game approach's benefits is to make strategic control decisions to fair-efficiently share the limited TVWS spectrum resource. This feature is contributed to maximize the device payoff based on the service preference. It leads to a significant payoff improvement of the proposed protocol. From the curves in Fig.4, we can confirm that our proposed scheme performs better than the existing *CDSS*, *HGSS* and *DMSS* schemes.

In Fig.5, we depict the device fairness for class I application services. The curves presented in Fig.5 clearly show that our proposed scheme, in general, appropriately maintains a higher fairness than other existing protocols.

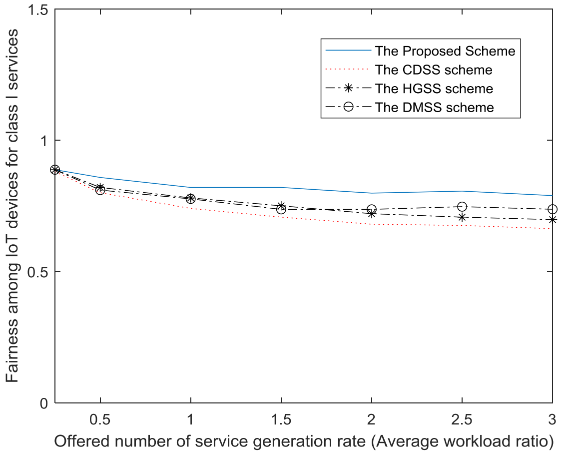


FIGURE 5. **Fairness among IoT devices for class I services.**

From the simulation results in Fig.3-Fig.5, it is evident that we can effectively compromise conflicting objectives to provide the most proper spectrum sharing solution for the TVWS infrastructure.

V. SUMMARY AND CONCLUSION

In this paper, we propose new inter and intra-bargaining games for the TVWS spectrum sharing problem. Based on the basic concept of *RIBS*, multiple IoT devices work together and act cooperatively with each other to effectively share the TVWS unlicensed spectrum. At the inter-bargaining process, the available spectrum resource is split for class I and class II application services based on the *RIBS* and *CEA* rule with $\mathbb{E}$. At the two intra-bargaining processes, the allocated spectrum resource for each type service is dynamically allocated for the corresponding IoT devices. For each intra-bargaining game, reference points are decided according to the *CEA* and *CEL* rules, and the idea of *RIBS* is also applied to solve the spectrum sharing problem. During the interactive operation, the main goal of our proposed bargaining model is to maximize the system performance while appropriately balancing the efficiency and fairness. Through the simulation analysis, it is concluded that our bargaining based approach can improve the overall system performance than the existing *CDSS*, *HGSS* and *DMSS* protocols under widely diversified data load intensities.

COMPETING OF INTERESTS

The author declares that there are no competing interests regarding the publication of this paper.

AVAILABILITY OF DATA AND MATERIAL

Please contact the corresponding author at *swkim01@sogang.ac.kr*.

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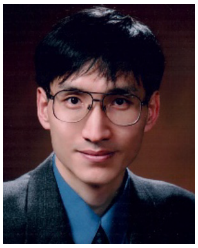

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