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Adaptive Multiservice Resource Allocation Algorithm With Wireless Network Virtualization

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ABSTRACT Wireless network virtualization (WNV) is emerging as a new paradigm to provide high speed communications and it is identified as one of the key enabling technologies to bring fifth-generation (5G) networks into fruition. With network slicing, physical networks are partitioned into multiple virtual networks to serve different types of service while satisfying their specific requirements. In this study, we present an adaptive spectrum control scheme for the WNV technology. Particularly, we develop a two-tier resource allocation algorithm to utilize a multi-service wireless network. In order to increase flexibility and independence among different network slices, our proposed approach is decoupled into two level bargaining games. These games are designed to solve the inter and intra slice resource allocation problems while ensuring traffic services with multiple requirements. Using four different bargaining solutions, we provide considerable benefits when network agents successfully cooperate and maintain an optimal performance balance. Simulation results and analyses are provided to reveal the effectiveness of our proposed approach compared with existing WNV based spectrum control protocols. Finally, we address some challenges and identify research areas for future studies.

INDEX TERMS Wireless network virtualization, 5G networks, bargaining solutions, cooperative game theory, multiservice resource allocation.

I. INTRODUCTION

With the explosive growth of demands for a variety of communication services, wireless traffic has experienced explosive growth in recent years. Based on market predictions, mobile data traffic will keep growing at an astonishing compound annual growth rate of 47 percent toward 2030. Moreover, the average year-on-year subscriber growths of 5%-15% are expected to continue well into the next decade. At the same time, user expectation on service quality also continues to increase, regardless of their location or network load conditions. In response to this traffic explosion, a number of technical studies aim at breaking the capacity bottleneck by densification. To promote network capacity, we can increase the deployment density of low-power small base stations; it is ultra-dense small cell network (UDNs). Recently, 5G network systems are expected to provide aggressively reuse spectrum through the UDN infrastructure [1], [2].

Throughout the 5G network's standardization, network densification has been the main driving force of cellular technology in the years to come, with the full integration of small cell technique in their specifications, and the commercial deployment of small cell products. However, it is important to realize that these new UDNs are fundamentally different from the traditional cellular networks, and thus UDNs cannot be deployed and operated in the same way as in the last 25 years. Therefore, UDNs are creating new and significant challenges for network system operators, and becoming increasingly complex with network planning and optimization techniques. For example, the scarce wireless spectrum resource and the network load imbalance in UDNs are the main challenges. Moreover, the operating and capital expenses are high because of the dense deployment of small base stations [1]–[3].

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Owing to these problems, network sharing mechanism is promising for future networks. It allows to share the infrastructure and wireless spectrum resource among wireless end users. In addition, the decoupling of services and infrastructures is necessary in order to meet more service demands. This approach can convert the service mode from physical to virtual entities while reducing expenses. Otherwise, it is difficult to bring in new technologies or adjust the existing technologies because of the complex composition of infrastructure providers (InPs). Therefore, virtualization for UDNs has been considered as a promising technology in 5G network era. By virtualization, the physical infrastructure and resources of UDNs can be completely abstracted, pooled, and integrated into many virtual resources, which then can be effectively shared to increase network capacity [2].

As a promising network sharing framework, wireless network virtualization (WNV) allows diverse services and applications to coexist on the common network infrastructure. Simply, the WNV technique can be interpreted as decoupling and sharing. Specifically, it is the process of combining hardware, software resources and network functionality to enable resource sharing and to decouple the infrastructure from the services it provides. With the WNV, physical resources, such as infrastructure, wireless spectrum, backhaul and fronthaul, of a base station (BS) owned by an InP are abstracted into isolated virtual resources, called slices. As wireless services providers, mobile virtual network operators (MVNOs) do not own their wireless network infrastructures and network resources; they transparently share the slices, and virtually owns the entire BS resources. Several benefits can be achieved through the WNV technology. First, the resource utilization can be improved through statistical multiplexing. Second, the deployment and operation expenses can be reduced through sharing. Third, service providers can enrich their services through virtualization [4], [5].

A. RESEARCH MOTIVATIONS

Even though the WNV technology has many advantages as a new control framework, there is still a major challenge, such as a designing of resource allocation process. In WNV, resource allocation means the problem of how to slice the physical resources for virtual networks to accommodate the dynamic demands of multiple MVNOs. This resource allocation problem is more challenging if network agents are self-interested. When each agent acts selfishly, it is very hard to achieve a desirable social efficiency. In this study, our main goal is to design a novel WNV resource allocation scheme, i) to boost network capacity, ii) to improve spectrum resource utilization, iii) to promote quality of service, and iv) to strike a performance balance. However, it is a complex and difficult work to satisfy these requirements. To overcome these challenges, a drastic change in control paradigm is required [1], [5].

In this study, we design a new spectrum control scheme with the WNV technology in the UDNs. Under a dynamically changing 5G network environment, it should provide inter and intra slice customization through efficient resource allocation. The major challenge of our proposed scheme is to coordinate the different MVNOs while ensuring good global properties. To the best of our knowledge, it is a hot research topic, but has not been well investigated. In our proposed scheme, autonomous, distributed, and intelligent MVNOs coordinately make rational and strategic decisions based on novel solution concepts. This scenario may fall into cooperative game theory. Cooperative game theory offers an effective model of cooperation between rational game players. The critical issue of cooperative games is how to distribute surplus outcome among all players. Therefore, various distribution solutions have been introduced by embodying different criteria [6].

B. TECHNICAL CONCEPTS

In cooperative game theory, bargaining solutions strive to understand the interplay between efficiency and fairness. Usually, bargaining solutions can be categorized into two different generalizations; one is proportional solution, and the other is Nash solution. For surplus sharing and rationing problems, proportional solution corresponds to the basic idea of Kalai-Smorodinsky solution. Depending on the kind of properties, Nash solution corresponds to the standard Nash bargaining idea. Under the assumption of unlimited liability, the proportional solution preserves the self-duality nature of equal losses solution for rationing problems and the equal-gains solution for surplus sharing problems, whereas the Nash solution preserves the idea of egalitarian allocations; it is defined by equal weighted net gains or losses from the entitlements point [7].

Usually, MVNOs may be concerned with the proportion of their claims that is satisfied, or with the total amount they get. In order to relate both perspectives, proportional bargaining solution is considered as a standard solution and the most widely used idea. The main reason is the fact that a proportional solution allows individuals to compare the treatment afforded to each one, in terms of the proportion of the claim that is honored. Therefore, from the viewpoint of relative fairness, the obtained amount per unit of individual claim is the same for all. As an interesting interpretation of proportionality in a conflicting claims problem, the egalitarian bargaining solution corresponds with the proportional rule, whereas when considering different reference points the Nash solution provides different loss rules in conflicting claims problems [8].

Since the 2000s, many research papers have taken a game theoretic approach to bankruptcy problems in terms of adequately generalized properties. They interpret the bankruptcy problem as the feasible set of a bargaining problem as introduced by J. Nash. This situation may be viewed as a theory of consensus, because it is often assumed that a final choice can be made if and only if every member of the group supports this choice. To explore the bargaining solutions with proportional ideas, different proportional solutions have been proposed such as *Weighted Kalai-Smorodinsky*

Bargaining Solution (*WKSBS*), *Claims based Proportional Solution* (*CPS*), *Truncated Proportional Solution* (*TPS*) and *Restricted Truncated Proportional Solution* (*RTPS*). Based on the bargaining game theory, these solutions derive new axiomatic characterizations, which concern changes in the claims. To implement the *WKSBS*, *CPS*, *TPS* and *RTPS*, individual utility is normalized in such a way that allocating nothing corresponds to a utility level of zero. Therefore, it is convenient to consider the zero vector as a natural benchmark for allocations instead of an exogenous disagreement point as within bargaining problems. The *WKSBS*, *CPS*, *TPS* and *RTPS* satisfy a number of appealing properties from the point of view of cooperative game theory [9], [14].

C. MAIN CONTRIBUTIONS

According to the main concept of proportional bargaining solutions, we develop a novel spectrum control scheme with the WNV technology. In the UDN platform, each individual MVNO fair-efficiently share the limited spectrum resource of each BS by considering the current traffic conditions. For the inter-MVNO slice allocation process, the inter-slice customization is operated based on the idea of *WKSBS*. For the intra-MVNO slice allocation process, the intra-slice customization is implemented according to the ideas of *CPS*, *TPS* and *RTPS*. These solutions work together toward an appropriately balanced system performance. Our interactive joint game approach provides the most proper combination of different bargaining solutions while ensuring good global properties. In detail, the major contributions of this study are as follows:

- This study considers the spectrum control problem in the WNV platform. During the interactive cooperative game paradigm, the control decisions for the resource allocation problems are made in an effective online fashion based on the different proportional bargaining solutions.
- At first-tier, multiple MVNOs fair-efficiently shares the BS's spectrum resource. To effectively coordinate MVNOs, we adopt the main characteristics of the *WKSBS*, and the inter-MVNO slice allocation process is dynamically operated based on the current conditions of MVNOs.
- At second-tier, each individual MVNO allocates its allocated spectrum resource for its corresponding devices. The *CPS*, *TPS* and *RTPS* solutions are used to implement intra-MVNO slice allocation processes by considering the heterogeneity of different traffic types.
- Under our two-tier bargaining procedure, we explore the interaction of *WKSBS*, *CPS*, *TPS* and *RTPS* while leveraging the synergistic features. The main novelty of our approach lies in the reciprocal combination of four different proportional bargaining solutions.
- We evaluate the performance of the proposed scheme via extensive experiments in a simulated environment. Our experimental results reveal that the proposed joint-bargaining approach can achieve a higher UDN system performance compared with the existing WNV based spectrum control protocols.

II. RELATED WORK

So far, there have been many types of research about WNV resource allocation problems in the academic community. L. Wang *et al.* propose the *Hierarchical Game based Resource Management* (*HGRM*) scheme for virtualized UDNs [2]. They formulate the virtual resource allocation problem as a hierarchical game and obtain the closed-form spectrum control solution. In the *HGRM* scheme, a two-layer architecture is presented to map the resource allocation problem from physical to virtual networks. And then, a hierarchical game is adapted to address matching interactions between resource providers and requests in the proposed two-layer architecture. To promote spectrum resource efficiency, a new low-complexity distributed customer-first algorithm is implemented, and the existence and uniqueness of equilibrium are analyzed for the *HGRM* scheme. Finally, simulation results confirm the effectiveness of the *HGRM* scheme in improving network performance while reducing the user access-reject probability [2].

The *Multi-scale Virtualized Resource Allocation* (*MVRA*) scheme is designed for the WNV platform, which is developed as a two time-scale hierarchical algorithm to reduce the complexity [4]. For the increasing independence among heterogeneous users, the InP virtualizes spectrum resources into three different types in large time period. At the begin of each small time slot, MVNOs assign their sub-channels to different users to maximize the total utility. To balance the tradeoff between the network stability and the system performance, the spectrum control problem is formulated as a mixed integer optimization problem. To tackle this problem, the *MVRA* scheme is implemented as a two-step process consisting of a heuristic sub-channel assignment method and a fast barrier method. By using Lyapunov drift-plus-penalty function, the original optimization problem is transformed into a Lyapunov optimization problem. Even though this approach does not fully consider the fairness among users, simulation results show the effectiveness of the *MVRA* scheme [4].

In [10], the *Multi-service Hierarchical Resource Allocation* (*MHRA*) scheme is developed with the WNV technology. Based on the three generic scenarios in 5G networks, the *MHRA* scheme is a two-dimension time scale resource allocation algorithm in the WNV platform. In order to increase flexibility while reducing the task complexity, the resource allocation problem is decoupled into two time scales: large time period for inter-MVNO resource allocation and small time slot for intra-MVNO resource scheduling. In the inter-MVNO resource process, the spectrum resource is virtualized to support services with multiple service requirements. Due to the different optimization objectives, it can be set up as a multi-objective optimization problem, which is solved by using the weighted Tchebycheff approach. In the intra-MVNO resource process, the allocated virtual resource is managed in every transmission time interval for a better performance. This process can be transformed into a delay-aware optimization problem, which is solved by using a distributed heuristic algorithm. Finally, the simulation results validate that the *MHRA* scheme has a good performance close to the optimal solution with a lower complexity [10].

The *HGRM*, *MVRA* and *MHRA* schemes have introduced unique challenges to efficiently solve the virtualized spectrum control problem. Recently, they have attracted considerable attention because of their various advantages. Although a number of researches on spectrum control problems in virtualized networks have been done, bargaining game based approach is still at the beginning level. To the best of our knowledge, we are the first to propose a two-tier bargaining model for the UDN spectrum control problem by applying the concept of virtualization. Compared to the existing *HGRM*, *MVRA* and *MHRA* schemes [2], [4], [10], we demonstrate that the proposed scheme achieves a better UDN system performance with the WNV technology.

III. THE SPECTRUM CONTROL SCHEME WITH WNV TECHNOLOGY

In this section, we first introduce the UDN system infrastructure, and explain the main ideas of the *WKSBS*, *CPS*, *TPS* and *RTPS*. Subsequently, our joint interactive bargaining model is formulated for the spectrum control process in the WNV platform. Finally, we explain the main steps of our proposed spectrum control algorithm.

A. The UDN system infrastructure with WNV

As illustrated in Fig. 1, we consider a UDN infrastructure with an InP including multiple BSs and wireless resources. $\mathbb{B} = \{\mathcal{B}_1, \mathcal{B}_2, \ldots, \mathcal{B}_n\}$ is the set of BSs, and $\mathcal{B}_i \in \mathbb{B}$ has its own spectrum resource, i.e., $\mathfrak{M}_{\mathcal{B}_i}$. The $\mathcal{B}_i$ provides its service to a set $\mathbb{N}_{\mathcal{B}_i}$ of IoT devices, which are covered by the $\mathcal{B}_i$. Then, $\mathbb{N} = \bigcup_{\mathcal{B}_i \in \mathbb{B}} \mathbb{N}_{\mathcal{B}_i}$ represents the total number of IoT devices in the multi-cell UDN system. We assume that individual IoT devices generate three different type services such as primary services (PSs), secondary services (SSs) and tertiary services (TSs). The PSs are latency-sensitive services like as self-driving and drone control, which need low-latency QoS requirements. The SSs are characterized by high data rate like as high definition videos and virtual reality with high transmission data rates. For connection density like as smart city and smart home, the TSs need a large number of local and temporary transmissions with no strict QoS requirements in capacity, latency, and reliability. The InP virtualizes each BS's spectrum resource into three slices, i.e., $\mathcal{S}_P$, $\mathcal{S}_S$ and $\mathcal{S}_T$, and assigns them for PSs, SSs, and TSs, respectively. In each BS, three MVNOs, i.e., $\mathcal{M}_P$, $\mathcal{M}_S$ and $\mathcal{M}_T$, are installed to share and operate the virtualized $\mathcal{S}_P$, $\mathcal{S}_S$ and $\mathcal{S}_T$, respectively [4], [10].

In our proposed scheme, we design a two-tier spectrum control process for UDNs. Without a loss of generality, we consider the $\mathcal{B}_i \in \mathbb{B}$ as an example. The $\mathcal{B}_i$ virtualizes its $\mathfrak{M}_{\mathcal{B}_i}$ into $\mathcal{S}_P^{\mathcal{B}_i}$, $\mathcal{S}_S^{\mathcal{B}_i}$ and $\mathcal{S}_T^{\mathcal{B}_i}$ where $\mathfrak{M}_{\mathcal{B}_i} \geq \left(\mathcal{S}_P^{\mathcal{B}_i} + \mathcal{S}_S^{\mathcal{B}_i} + \mathcal{S}_T^{\mathcal{B}_i}\right)$, and assigns these slices for its corresponding traffic services. For the $\mathcal{B}_i$, our proposed scheme consists of two tiers. At the first tier, the inter-slice spectrum allocation problem is formulated as the game $\mathbb{G}_{\mathcal{B}_i}$. In this game, the $\mathcal{M}_P$, $\mathcal{M}_S$ and $\mathcal{M}_T$ work together to solve the matching problem of slice demands and physical spectrum resource $\left(\mathfrak{M}_{\mathcal{B}_i}\right)$ in the $\mathcal{B}_i$. At the second tier, the intra-slice scheduling problem for each type service is modeled as three games such as $\mathbb{G}_{\mathcal{B}_i}^{\mathcal{M}_P}$, $\mathbb{G}_{\mathcal{B}_i}^{\mathcal{M}_S}$, and $\mathbb{G}_{\mathcal{B}_i}^{\mathcal{M}_T}$. For these games, the $\mathcal{M}_P$, $\mathcal{M}_S$ and $\mathcal{M}_T$ work independently in a distributed fashion. Based on service types, they schedule their assigned $\mathcal{S}_P$, $\mathcal{S}_S$ and $\mathcal{S}_T$ slices to their corresponding PSs, SSs, and TSs, respectively. Under dynamically changing traffic environments, a fixed spectrum allocation and scheduling approach cannot effectively adapt to current UDN conditions. Therefore, the $\mathcal{M}_P$, $\mathcal{M}_S$ and $\mathcal{M}_T$ must be dynamically adjustable. To satisfy this goal, we design a joint interactive bargaining game $(\mathbb{G})$ in a coordination manner; $\mathbb{G}$ is subdivided into two-tier subgames; $\mathbb{G}_{\mathcal{B}_i \in \mathbb{B}}$, $\mathbb{G}_{\mathcal{B}_i}^{\mathcal{M}_P}$, $\mathbb{G}_{\mathcal{B}_i}^{\mathcal{M}_S}$, and $\mathbb{G}_{\mathcal{B}_i}^{\mathcal{M}_T}$. And, different bargaining solutions are adopted to effectively solve each bargaining games. Formally, we define game entities, i.e., $\mathbb{G} = \left\{\mathcal{B}_i \in \mathbb{B} | \mathbb{G}_{\mathcal{B}_i}, \mathbb{G}_{\mathcal{B}_i}^{\mathcal{M}_P}, \mathbb{G}_{\mathcal{B}_i}^{\mathcal{M}_S}, \mathbb{G}_{\mathcal{B}_i}^{\mathcal{M}_T}\right\} =$

$$\left\{\mathbb{B}, \mathbb{N}, \left\{\mathbb{G}_{\mathcal{B}_i} \middle| \begin{matrix} \mathfrak{M}_{\mathcal{B}_i}, \mathbb{N}_{\mathcal{B}_i}, \left(\mathcal{M}_P, \mathcal{M}_S, \mathcal{M}_T\right), \left(\mathcal{S}_P^{\mathcal{B}_i}, \mathcal{S}_S^{\mathcal{B}_i}, \mathcal{S}_T^{\mathcal{B}_i}\right), \\ \left(U_{\mathcal{M}_P}(\cdot), U_{\mathcal{M}_S}(\cdot), U_{\mathcal{M}_T}(\cdot)\right) \end{matrix} \right\}, \right.$$
$$\left\{\mathbb{G}_{\mathcal{B}_i}^{\mathcal{M}_P} | \mathcal{M}_P, D_j^{\mathcal{B}_i,P} \in \mathbb{N}_{\mathcal{B}_i}^P, \mathcal{S}_j^{\mathcal{B}_i,P}, \mathfrak{U}_j^{\mathcal{B}_i,P}(\cdot)\right\},$$
$$\left\{\mathbb{G}_{\mathcal{B}_i}^{\mathcal{M}_S} | \mathcal{M}_S, D_k^{\mathcal{B}_i,S} \in \mathbb{N}_{\mathcal{B}_i}^S, \mathcal{S}_k^{\mathcal{B}_i,S}, \mathfrak{U}_k^{\mathcal{B}_i,S}(\cdot)\right\},$$
$$\left. \left\{\mathbb{G}_{\mathcal{B}_i}^{\mathcal{M}_T} | \mathcal{M}_T, D_l^{\mathcal{B}_i,T} \in \mathbb{N}_{\mathcal{B}_i}^T, \mathcal{S}_l^{\mathcal{B}_i,T}, \mathfrak{U}_l^{\mathcal{B}_i,T}(\cdot)\right\}, \mathbb{T}\right\}$$

of gameplay.

- $\mathbb{G}_{\mathcal{B}_i}$, $\mathbb{G}_{\mathcal{B}_i}^{\mathcal{M}_P}$, $\mathbb{G}_{\mathcal{B}_i}^{\mathcal{M}_S}$, and $\mathbb{G}_{\mathcal{B}_i}^{\mathcal{M}_T}$ are bargaining games for the $\mathcal{B}_i$, and they are mutually and reciprocally interdependent in an interactive manner.
- $\mathbb{B}$ and $\mathbb{N}$ are the sets of all BSs and IoT devices. For the $\mathcal{B}_i \in \mathbb{B}$, $\mathfrak{M}_{\mathcal{B}_i}$ is the $\mathcal{B}_i$'s physical spectrum resource, and $\mathbb{N}_{\mathcal{B}_i} \subset \mathbb{N}$ is the set of IoT devices covered by the $\mathcal{B}_i$.
- In the $\mathbb{G}_{\mathcal{B}_i}$, $\mathcal{M}_P$, $\mathcal{M}_S$ and $\mathcal{M}_T$ are game players, and the amounts of $\mathcal{S}_P^{\mathcal{B}_i}$, $\mathcal{S}_S^{\mathcal{B}_i}$ and $\mathcal{S}_T^{\mathcal{B}_i}$ are their strategies. $U_{\mathcal{M}_P}(\cdot)$, $U_{\mathcal{M}_S}(\cdot)$ and $U_{\mathcal{M}_T}(\cdot)$ are utility functions for the $\mathcal{M}_P$, $\mathcal{M}_S$ and $\mathcal{M}_T$, respectively.

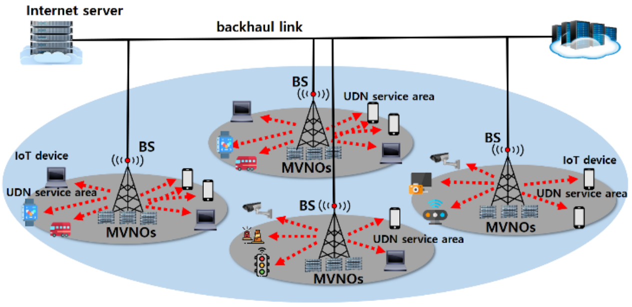

FIGURE 1. The UDN system infrastructure with WNV.

- In the $\mathbb{G}_{\mathcal{B}_i}^{\mathcal{M}_P}$, $\mathbb{N}_{\mathcal{B}_i}^{P}$ is the set of devices, which run PSs in the $\mathcal{B}_i$. Each device $D_j^{\mathcal{B}_i,P} \in \mathbb{N}_{\mathcal{B}_i}^{P}$ is a game player, and $\mathcal{S}_j^{\mathcal{B}_i,P}$ is the assigned spectrum amount for the $D_j^{\mathcal{B}_i,P}$; it is the strategy of $D_j^{\mathcal{B}_i,P}$. $\mathfrak{U}_j^{\mathcal{B}_i,P}(\cdot)$ is the $D_j^{\mathcal{B}_i,P}$'s utility function where $\mathcal{S}_P^{\mathcal{B}_i} \geq \sum_{D_j^{\mathcal{B}_i,P} \in \mathbb{N}_{\mathcal{B}_i}^{P}} \mathcal{S}_j^{\mathcal{B}_i,P}$.
- In the $\mathbb{G}_{\mathcal{B}_i}^{\mathcal{M}_S}$, $\mathbb{N}_{\mathcal{B}_i}^{S}$ is the set of devices, which run SSs in the $\mathcal{B}_i$. Each device $D_k^{\mathcal{B}_i,S} \in \mathbb{N}_{\mathcal{B}_i}^{S}$ is a game player, and $\mathcal{S}_k^{\mathcal{B}_i,S}$ is the assigned spectrum amount for the $D_k^{\mathcal{B}_i,S}$; it is the strategy of $D_k^{\mathcal{B}_i,S}$. $\mathfrak{U}_j^{\mathcal{B}_i,S}(\cdot)$ is the $D_k^{\mathcal{B}_i,S}$'s utility function where $\mathcal{S}_S^{\mathcal{B}_i} \geq \sum_{D_k^{\mathcal{B}_i,S} \in \mathbb{N}_{\mathcal{B}_i}^{S}} \mathcal{S}_k^{\mathcal{B}_i,S}$.
- In the $\mathbb{G}_{\mathcal{B}_i}^{\mathcal{M}_T}$, $\mathbb{N}_{\mathcal{B}_i}^{T}$ is the set of devices, which run TSs in the $\mathcal{B}_i$. Each device $D_l^{\mathcal{B}_i,T} \in \mathbb{N}_{\mathcal{B}_i}^{T}$ is a game player, and $\mathcal{S}_l^{\mathcal{B}_i,T}$ is the assigned spectrum amount for the $D_l^{\mathcal{B}_i,T}$; it is the strategy of $D_l^{\mathcal{B}_i,T}$. $\mathfrak{U}_l^{\mathcal{B}_i,T}(\cdot)$ is the $D_l^{\mathcal{B}_i,T}$'s utility function where $\mathcal{S}_T^{\mathcal{B}_i} \geq \sum_{D_l^{\mathcal{B}_i,T} \in \mathbb{N}_{\mathcal{B}_i}^{P}} \mathcal{S}_l^{\mathcal{B}_i,T}$.
- $\mathbb{T} = \{t_1, \ldots, t_c, t_{c+1}, \ldots\}$ denotes time, which is represented by a sequence of time steps.

B. BARGAINING SOLUTIONS FOR COOPERATIVE GAME MODELS

The cooperative game theory will serve as a very convenient template for the theory of bargaining with claims. In 1950, J. Nash proposed Nash bargaining solution based on axioms pertaining to changes in the feasible set. In the Nash traditional bargaining model, the outcome of a negotiation is a function only of the bargaining set and the disagreement point. It has been noted by a number of literatures that other aspects of the environment influence the outcome of the bargain. Recently, the focus has shifted to the proportional bargaining solution. This approach can be fruitfully adapted to develop the basic idea of Kalai-Smorodinsky solution; the utility gains at the compromise are proportional to what they would be at the ideal point, the point whose ith coordinate is the maximal utility the player i could obtain in the part of bargaining set [11].

To characterize the basic concepts of proportional bargaining solutions, we preliminarily define some mathematical expressions. The nonempty and finite set $N = \{1, \ldots, n\}$ will denote the game player set. $\mathbb{R}$ $(\mathbb{R}_+, \mathbb{R}_{++})$ denote the set of all (non-negative, positive) real numbers and let $\mathbb{R}^n$ $\left(\mathbb{R}_+^n,\ \mathbb{R}_{++}^n\right)$ be the n-fold Cartesian product of $\mathbb{R}$ $(\mathbb{R}_+, \mathbb{R}_{++})$. Vector inequalities in $\mathbb{R}^n$ are denoted by $\geq, >, \gg$. For any $x,\ y \in \mathbb{R}_+^N$, $x \leq y$ denotes $x_i \leq y_i$ for all $i \in N$, and $x < y$ denotes $x_i < y_i$ for all $i \in N$. The zero-vector $x \in \mathbb{R}_+^N$ with $x_i = 0$ for all $i \in N$ is denoted by 0_N. $E \subseteq \mathbb{R}_+^N$ is the set of attainable utility allocations where $E = \left\{x \in \mathbb{R}_+^N | \exists_{y \in E} : y \geq x\right\}$. Elements of E are assumed to be normalized such that allocating nothing to a player corresponds to zero utility. Let c be the vector of claims of N on E where $c \in \mathbb{R}_+^N$ with $c \not\leq x$ for all $x \in E$. The claim vector c represents the individual utility claims on the resource. With the limited resource amount $M \in \mathbb{R}_+$, a bargaining problem is denoted by (N, E, c) where $E = \left\{x \in \mathbb{R}_+^N | \sum_{i \in N} x_i \leq M\right\}$, $c \notin E$ and $E \neq \{0_N\}$. Let $(N, E, c) \in \Sigma^n$ and a solution is a function $f : \Sigma^n \to \mathbb{R}^n$ that associates a unique point of E, $f(N, E, c)$, called the solution outcome of (N, E, c) [12].

For any $t \in \mathbb{R}_{++}$, the set $(t \cdot E) \subseteq \mathbb{R}_+^N$ is defined by $(t \cdot E) = \{t \cdot x |\ x \in E\}$. Note that $u^{t \cdot E} = t \cdot u^E$ for all $t \in \mathbb{R}_{++}$. For any set of payoff allocations $E \subseteq \mathbb{R}_{++}^n$, u^E is the vector of utopia values; it is given by $u^E = (\mathbf{max}\{x_i | x \in E\})_{i \in N}$ where $u^E \in \mathbb{R}_{++}^N$. $\hat{c}^E$ is the vector of truncated claims; it is given by $\hat{c}^E = \left(\mathbf{min}\left\{c_i, u_i^E\right\}\right)_{i \in N}$ where $\hat{c}^E \in \mathbb{R}_{++}^N$. The following solution definitions are *WKSBS*, *CPS*, *TPS* and *RTPS* [12], [13].

Definition 1: The *WKSBS* for all $(N, E, c) \in \Sigma^n$ is *WKSBS*$(N, E, \left(\mathcal{W} \cdot u^E\right))$, which is the maximal point of E on the segment connecting $d = \{0_N\}$ and weighted utopian point. To express it as a mathematical formula type, $WKSBS\left(N, E, \left(\mathcal{W} \cdot u^E\right)\right) = \left(\lambda^{WKSBS} \cdot \left(\mathcal{W} \cdot u^E\right)\right)$ where $\lambda^{WKSBS} = \mathbf{max}\left\{t \in (0, 1] | \left(t \cdot u^E\right) \in E\right\}$ and $\mathcal{W}$ is a weight vector.

Definition 2: The *CPS* for all $(N, E, c) \in \Sigma^n$ is *CPS*(N, E, c), which is the maximal point of E on the segment connecting $d = \{0_N\}$ and c. To express it as a mathematical formula type, $CPS\,(N, E, c) = \left(\lambda^{CPS} \cdot c\right)$ where $\lambda^{CPS} = \mathbf{max}\{t \in (0, 1] | (t \cdot c) \in E\}$.

Definition 3: The *TPS* for all $(N, E, c) \in \Sigma^n$ is *TPS*$(N, E, \hat{c}^E)$, which is the maximal point of E on the segment connecting $d = \{0_N\}$ and $\hat{c}^E$. Therefore, $TPS\left(N, E, \hat{c}^E\right) = \left(\lambda^{CPS} \cdot \hat{c}^E\right)$.

Definition 4: If $c < u^E$, the *RTPS* for all $(N, E, c) \in \Sigma^n$ is the maximal point of E on the segment connecting $d = \{0_N\}$ and c. Therefore, $RTPS\,(N, E, c) = \left(\lambda^{CPS} \cdot c\right) = CPS\,(N, E, c)$. Otherwise, if $c \geq u^E$, *RTPS*(N, E, c) is $\left(\left(t \cdot u_S^E\right),\ 0_{N \setminus S}\right)$ where $S = \left\{i \in N | c_i \geq u_i^E\right\}$ and $t \in (0, 1]$.

The *WKSBS*, *CPS*, *TPS* and *RTPS* are characterized by a collection of desirable axioms like as, *relative symmetry* (***RS***), *step-by-step negotiations* (***SSN***), *estate monotonicity* (***EM***), *domination* (***D***), *independence of irrelevant alternatives* (***IIA***), *independence of undominating alternatives* (***IUdA***), *independence of unclaimed alternatives* (***IUcA***), *truncation invariance* (***TI***), *claims continuity* (***CC***), *weak claims linearity* (***WCL***), *claims convexity* (***Cc***), *weak claims convexity* (***WCc***), and *positive awards* (***PA***). The *WKSBS* is characterized by a collection of desirable axioms ***RS***, ***SSN***, ***EM***. The *CPS* is characterized by a collection of desirable axioms ***RS***, ***SSN***, ***EM***, ***D***, ***IIA***, ***IUdA***, ***IUcA***, ***CC***, ***WCL***, ***Cc***, ***WCc*** and ***PA***. The *TPS* is characterized by a collection of desirable axioms ***RS***, ***TI***, ***IUcA***, ***CC*** and ***PA***. The *RTPS* is characterized by a collection of desirable axioms ***RS***, ***TI*** and ***IUcA*** [13].

- ***RS:*** if $\left(f_i(E, c)/u_i^E\right) = \left(f_j(E, c)/u_j^E\right)$ for all $(E, c) \in \Sigma^n$ and any $i, j \in N$ for which $\left(c_i/u_i^E\right) = \left(c_j/u_j^E\right)$.

- ***SSN:*** if $f(E,c) = f(E',c) + f\left(\left(E - \{f(E',c)\}\right)_+, c - f(E',c)\right)$ for all $(E,c), (E',c) \in \Sigma^n$ for which $E' \subseteq E$. Here, $\left(E - \{f(E',c)\}\right)_+ = \left\{x \in \mathbb{R}_+^N \mid x + f(E',c) \in E\right\}$.
- ***EM:*** if $f(E,c) \geq f(E',c)$ for all $(E,c), (E',c) \in \Sigma^n$ for which $E' \subseteq E$.
- ***D:*** if $f(E,c) \leq f(E',c)$ *or* $f(E,c) \geq f(E',c)$ *for all* $(E,c), (E',c) \in \Sigma^n$.
- ***IIA:*** $f(E,c) = f(E',c)$ for all $(E,c), (E',c) \in \Sigma^n$ for which $E' \subseteq E$ and $f(E,c) \in WP(E') = \left\{x \in E' \mid \neg\exists_{y \in E'} : y > x\right\}$.
- ***IUdA:*** if $f(E,c) = f(E',c)$ for all $(E,c), (E',c) \in \Sigma^n$ for which $E' \subseteq E$ and $f(E',c) \in WP(E) = \left\{x \in E \mid \neg\exists_{y \in E} : y > x\right\}$.
- ***IUcA:*** if $f(E,c) = f(E',c)$ for all $(E,c), (E',c) \in \Sigma^n$ for which $\hat{E}_c \subseteq \hat{E}'_c$.
- ***TI:*** if $f(E,c) = f(E, \hat{c}^E)$ for all $(E,c) \in \Sigma^n$.
- ***CC:*** if $f(E,c)$ is continuous in c for all $(E,c) \in \Sigma^n$.
- ***WCL:*** if $f(E,c) = f(E, ((\theta \cdot c) + ((1-\theta) \cdot f(E,c))))$ for all $(E,c) \in \Sigma^n$ and any $\theta \in \mathbb{R}_{++}$.
- ***Cc:*** if $f(E,c) = f\left(E, \left((\theta \cdot c) + \left((1-\theta) \cdot c'\right)\right)\right)$ for all $(E,c), (E,c') \in \Sigma^n$ for which $f(E,c) = f(E,c')$ and any $\theta \in [0,1]$.
- ***WCc:*** if $f(E,c) = f(E, ((\theta \cdot c) + ((1-\theta) \cdot f(E,c))))$ for all $(E,c) \in \Sigma^n$ and any $\theta \in [0,1]$.
- ***PA:*** for all $(E,c) \in \Sigma^n, f_{N_+^c}(E,c) > 0_{N_+^c}$ where $N_+^c = \{i \in N | c_i > 0\}$ is the set of positive claimants.

C. THE PROPOSED SPECTRUM CONTROL SCHEME IN THE UDNs

In the UDN infrastructure, the InP virtualizes all base stations' spectrum resources with WNV technology. Each individual base station operate its two-tier game ($\mathbb{G}$) in a distributed manner. In the viewpoint of $\mathcal{B}_i \in \mathbb{B}$, we explain the procedure of $\mathbb{G}$, which consists of $\mathbb{G}_{\mathcal{B}_i}$, $\mathbb{G}_{\mathcal{B}_i}^{\mathcal{M}_P}$, $\mathbb{G}_{\mathcal{B}_i}^{\mathcal{M}_S}$, and $\mathbb{G}_{\mathcal{B}_i}^{\mathcal{M}_T}$. In the $\mathbb{G}_{\mathcal{B}_i}$, three MVNOs, i.e., $\mathcal{M}_P$, $\mathcal{M}_S$ and $\mathcal{M}_T$, are game players, who need $\mathcal{S}_P$, $\mathcal{S}_S$ and $\mathcal{S}_T$ slices to ensure their services. The utility payoff obtained by each MVNO depends on the current traffic flow and the amount of allocated slice. According to the satisfaction from MVNOs, the utility functions of $\mathcal{M}_P$, $\mathcal{M}_S$, $\mathcal{M}_T$, that is, $U_{\mathcal{M}_P}(\cdot), U_{\mathcal{M}_S}(\cdot), U_{\mathcal{M}_T}(\cdot)$, are derived as follows:

$$\begin{cases} U_{\mathcal{M}_P}\left(\mathcal{S}_P^{\mathcal{B}_i}, R_P^{\mathcal{B}_i}\right) = \chi \times \left(\sigma - exp\left(-\eta \times \frac{\mathbf{min}\left(\mathcal{S}_P^{\mathcal{B}_i}, R_P^{\mathcal{B}_i}\right)}{R_P^{\mathcal{B}_i}}\right)\right). \\ U_{\mathcal{M}_S}\left(\mathcal{S}_S^{\mathcal{B}_i}, R_S^{\mathcal{B}_i}\right) = \dfrac{\varepsilon}{\xi + exp\left(-\frac{\mathbf{min}\left(\mathcal{S}_S^{\mathcal{B}_i}, R_S^{\mathcal{B}_i}\right)}{R_S^{\mathcal{B}_i}}\right)} - \zeta. \\ U_{\mathcal{M}_T}\left(\mathcal{S}_T^{\mathcal{B}_i}, R_T^{\mathcal{B}_i}\right) = \gamma \times log\left(\dfrac{\mathbf{min}\left(\mathcal{S}_T^{\mathcal{B}_i}, R_T^{\mathcal{B}_i}\right)}{R_T^{\mathcal{B}_i}} + \Delta\right). \end{cases}$$

$$\text{s.t., } \mathfrak{M}_{\mathcal{B}_i} \geq \left(\mathcal{S}_P^{\mathcal{B}_i} + \mathcal{S}_S^{\mathcal{B}_i} + \mathcal{S}_T^{\mathcal{B}_i}\right) \tag{1}$$

where χ, σ, η are control parameters for $U_{\mathcal{M}_P}(\cdot)$, ξ, ε, ζ are system adjustment factors for $U_{\mathcal{M}_S}(\cdot)$, and γ, Δ are control parameters for $U_{\mathcal{M}_T}(\cdot)$. $R_P^{\mathcal{B}_i}$, $R_S^{\mathcal{B}_i}$, $R_T^{\mathcal{B}_i}$ are the requested amount from the $\mathcal{M}_P$, $\mathcal{M}_S$, $\mathcal{M}_T$, respectively. To implement our spectrum allocation algorithm, we concern the different characteristics of PSs, SSs, and TSs. Therefore, we should treat asymmetrically the PSs, SSs, and TSs. Usually, one main feature of traditional bargaining solutions is *Symmetry*. However, assuming *Symmetry* is unreasonable for the first-tier spectrum allocation problem; imposing *Symmetry* can mean, assuming equality of bargaining skill among the PSs, SSs, and TSs. In order to mediate the particularity of different traffic services, we adopt the idea of *WKSBS* by relaxing *Symmetry*, and make the solution more flexible [14]. Therefore, the idea of *WKSBS* is adopted for the solution of $\mathbb{G}_{\mathcal{B}_i}$; it is given by:

$$\begin{aligned} & WKSBS_{\mathbb{G}_{\mathcal{B}_i}}\left(\mathcal{M}, \mathcal{S}, \mathcal{W}_{\mathcal{M}}, U_{\mathcal{M}}^*\right) \\ & = \left\{U_{\mathcal{M}}^* = \left(U_{\mathcal{M}_P}^*, U_{\mathcal{M}_S}^*, U_{\mathcal{M}_T}^*\right) \middle| \left(\lambda^{WKSBS} \cdot \left(\mathcal{W}_{\mathcal{M}} \cdot U_{\mathcal{M}}^*\right)\right)\right\}. \\ & s.t.,\ \lambda^{WKSBS} \\ & = \mathbf{max}\left\{t \in (0,1] \middle| \left(\mathcal{S}_P^{\mathcal{B}_i} + \mathcal{S}_S^{\mathcal{B}_i} + \mathcal{S}_T^{\mathcal{B}_i}\right) \leq \mathfrak{M}_{\mathcal{B}_i}\right\} \end{aligned} \tag{2}$$

where $\mathcal{W}_{\mathcal{M}}$ and $U_{\mathcal{M}}^*$ are the vectors of weights and utopia values for MVNOs, respectively. According to (2), the values of $\mathcal{S}_P^{\mathcal{B}_i}$, $\mathcal{S}_S^{\mathcal{B}_i}$ and $\mathcal{S}_T^{\mathcal{B}_i}$ are obtained. Based on the result of $\mathbb{G}_{\mathcal{B}_i}$, the second-tier spectrum scheduling algorithm is operated. Independently, individual MVNOs schedule their slices for their corresponding devices. Using the $\mathcal{S}_P^{\mathcal{B}_i}$, the $\mathbb{G}_{\mathcal{B}_i}^{\mathcal{M}_P}$ is designed to support multiple PSs. In the $\mathbb{G}_{\mathcal{B}_i}^{\mathcal{M}_P}$, devices in the $\mathbb{N}_{\mathcal{B}_i}^P$, i.e., $D_j^{\mathcal{B}_i,P} \in \mathbb{N}_{\mathcal{B}_i}^P$, are game players and the scheduled spectrum amount for the $D_j^{\mathcal{B}_i,P}$, i.e., $\mathcal{S}_j^{\mathcal{B}_i,P}$, is his strategy. The utility function of $D_j^{\mathcal{B}_i,P}$, i.e., $\mathfrak{U}_j^{\mathcal{B}_i,P}(\cdot)$, is defined as follows:

$$\begin{aligned} & \mathfrak{U}_j^{\mathcal{B}_i,P}\left(\mathcal{S}_j^{\mathcal{B}_i,P}, R_j^{\mathcal{B}_i,P}, \mathbb{N}_{\mathcal{B}_i}^P\right) \\ & \qquad = \left(\delta - exp\left(\theta \times \frac{\mathbf{min}\left(\mathcal{S}_j^{\mathcal{B}_i,P}, R_j^{\mathcal{B}_i,P}\right)}{R_j^{\mathcal{B}_i,P}}\right)\right). \end{aligned} \tag{3}$$

where α, δ, θ are control parameters for $\mathfrak{U}_j^{\mathcal{B}_i,P}(\cdot)$. From the viewpoint of the $\mathcal{M}_P$, PSs should be operated monotonically due to the feature of latency sensitivity. Therefore, ***SSN***, ***EM***, ***D*** and ***IIA*** axioms are more desirable, hence we adopt the *CPS* for the solution of $\mathbb{G}_{\mathcal{B}_i}^{\mathcal{M}_P}$. According to each service request, devices in the $\mathbb{N}_{\mathcal{B}_i}^P$ have their claims, which simply maximize their payoffs. With their claims, the $\mathcal{S}_j^{\mathcal{B}_i,P}$ value is decided by using the concept of the *CPS*. For the $\mathbb{G}_{\mathcal{B}_i}^{\mathcal{M}_P}$, the *CPS* is given by:

$$\begin{aligned} & CPS_{\mathbb{G}_{\mathcal{B}_i}^{\mathcal{M}_P}}\left(\mathbb{N}_{\mathcal{B}_i}^P, \mathcal{S}_P^{\mathcal{B}_i}, c_{\mathbb{N}_{\mathcal{B}_i}^P}\right) \\ & \qquad = \left\{c_{\mathbb{N}_{\mathcal{B}_i}^P} = \left(\ldots c_{D_j^{\mathcal{B}_i,P} \in \mathbb{N}_{\mathcal{B}_i}^P} \ldots\right) \middle| \left(\lambda_P^{CPS} \cdot c_{\mathbb{N}_{\mathcal{B}_i}^P}\right)\right\}. \end{aligned}$$

$$\text{s.t., } \lambda_P^{CPS} = \mathbf{max}\left\{ t \in (0,1] \middle| \sum\nolimits_{D_j^{\mathcal{B}_i,P} \in \mathbb{N}_{\mathcal{B}_i}^P} \mathcal{S}_j^{\mathcal{B}_i,P} \le \mathcal{S}_P^{\mathcal{B}_i} \right\} \tag{4}$$

where $c_{D_j^{\mathcal{B}_i,P}}$ is the claim of $D_j^{\mathcal{B}_i,P}$; it is given by $\mathfrak{U}_j^{\mathcal{B}_i,P}(\cdot)$ with $\mathcal{S}_j^{\mathcal{B}_i,P} = R_j^{\mathcal{B}_i,P}$. According to (4), the $\mathcal{S}_j^{\mathcal{B}_i,P}$ is obtained for the PS of $D_j^{\mathcal{B}_i,P}$. For the $\mathcal{S}_S^{\mathcal{B}_i}$ scheduling process, the $\mathbb{G}_{\mathcal{B}_i}^{\mathcal{M}_S}$ is designed to support multiple SSs. In the $\mathbb{G}_{\mathcal{B}_i}^{\mathcal{M}_S}$, devices in the $\mathbb{N}_{\mathcal{B}_i}^S$, i.e., $D_k^{\mathcal{B}_i,S} \in \mathbb{N}_{\mathcal{B}_i}^S$, are game players and the scheduling spectrum amount for the $D_k^{\mathcal{B}_i,S}$, i.e., $\mathcal{S}_k^{\mathcal{B}_i,S}$, is his strategy. The utility function of $D_k^{\mathcal{B}_i,S}$, i.e., $\mathfrak{U}_k^{\mathcal{B}_i,S}(\cdot)$, is defined as follows:

$$\mathfrak{U}_k^{\mathcal{B}_i,S}\left(\mathcal{S}_k^{\mathcal{B}_i,S}, R_k^{\mathcal{B}_i,S}, \mathbb{N}_{\mathcal{B}_i}^S\right) = \frac{\phi}{\beta + exp\left(\rho \times \frac{min\left(\mathcal{S}_k^{\mathcal{B}_i,S}, R_k^{\mathcal{B}_i,S}\right)}{R_k^{\mathcal{B}_i,S}}\right)} - \omega. \tag{5}$$

where $\phi, \beta, \rho, \omega$ are control parameters for $\mathfrak{U}_k^{\mathcal{B}_i,S}(\cdot)$. Owning to the high data rate characterization, the $\mathcal{M}_S$ focuses on the axioms of ***CC*** and ***PA***. Therefore, we accept the concept of *TPS* for the $\mathbb{G}_{\mathcal{B}_i}^{\mathcal{M}_S}$, and it is obtained as follows:

$$\begin{aligned} &TPS_{\mathbb{G}_{\mathcal{B}_i}^{\mathcal{M}_S}}\left(\mathbb{N}_{\mathcal{B}_i}^S, \mathcal{S}_S^{\mathcal{B}_i}, \hat{c}_{\mathbb{N}_{\mathcal{B}_i}^S}\right) \\ &\quad = \left\{ \hat{c}_{\mathbb{N}_{\mathcal{B}_i}^S} = \left(\ldots \hat{c}^{S,D_k^{\mathcal{B}_i,S} \in \mathbb{N}_{\mathcal{B}_i}^S} \ldots\right) \middle| \left(\lambda_S^{TPS} \cdot \hat{c}_{\mathbb{N}_{\mathcal{B}_i}^S}\right) \right\}. \\ &\boldsymbol{s.t.,}\ \boldsymbol{\lambda_S^{TPS}} = \boldsymbol{max}\left\{ \boldsymbol{t \in (0,1]} | \sum\nolimits_{\boldsymbol{D_k^{\mathcal{B}_i,S}} \in \mathbb{N}_{\mathcal{B}_i}^S} \mathcal{S}_{\boldsymbol{k}}^{\mathcal{B}_i,\boldsymbol{S}} \le \mathcal{S}_{\boldsymbol{S}}^{\mathcal{B}_i} \right\} \end{aligned} \tag{6}$$

where $\hat{c}^{S,D_k^{\mathcal{B}_i,S}}$ is the truncated claim of $D_k^{\mathcal{B}_i,S}$; it is given to ensure the device's SSs. For the $\mathcal{S}_T^{\mathcal{B}_i}$ scheduling process, the $\mathbb{G}_{\mathcal{B}_i}^{\mathcal{M}_T}$ is designed to support multiple TSs. In the $\mathbb{G}_{\mathcal{B}_i}^{\mathcal{M}_T}$, devices in the $\mathbb{N}_{\mathcal{B}_i}^T$, i.e., $D_l^{\mathcal{B}_i,T} \in \mathbb{N}_{\mathcal{B}_i}^T$, are game players and the scheduling spectrum amount for the $D_l^{\mathcal{B}_i,T}$, i.e., $\mathcal{S}_l^{\mathcal{B}_i,T}$, is his strategy. The utility function of $D_l^{\mathcal{B}_i,T}$, i.e., $\mathfrak{U}_l^{\mathcal{B}_i,T}(\cdot)$, is defined as follows:

$$\mathfrak{U}_l^{\mathcal{B}_i,T}\left(\mathcal{S}_l^{\mathcal{B}_i,T}, R_l^{\mathcal{B}_i,T}\right) = \mu \times \log\left(\frac{\mathbf{min}\left(\mathcal{S}_l^{\mathcal{B}_i,T}, R_l^{\mathcal{B}_i,T}\right)}{R_l^{\mathcal{B}_i,T}} + \tau\right). \tag{7}$$

where μ, τ are control parameters for $\mathfrak{U}_k^{\mathcal{B}_i,T}(\cdot)$. To support TSs, we need a large number of temporary transmissions with no strict QoS requirement. Therefore, the $\mathcal{M}_T$ strongly emphasizes the restricted truncated proportionality. Therefore, we use the approach of *RTPS* for the $\mathbb{G}_{\mathcal{B}_i}^{\mathcal{M}_T}$, and it is given by: Devices in the $\mathbb{N}_{\mathcal{B}_i}^T$ have also their truncated claims $\left(\hat{c}^{T,D_l}\right)$ to ensure their TSs. With their truncated claims, the $\mathcal{S}_l^{\mathcal{B}_i,T}$ value is decided by using the concept of the *RTPS*. For the $\mathbb{G}_{\mathcal{B}_i}^{\mathcal{M}_T}$, the *RTPS*;

$$\begin{aligned} &RTPS_{\mathbb{G}_{\mathcal{B}_i}^{\mathcal{M}_T}}\left(\mathbb{N}_{\mathcal{B}_i}^T, \mathcal{S}_T^{\mathcal{B}_i}, c_{\mathbb{N}_{\mathcal{B}_i}^T}\right) \\ &= \begin{cases} \left\{ c_{\mathbb{N}_{\mathcal{B}_i}^T} = \left(\ldots c_{D_l^{\mathcal{B}_i,T} \in \mathbb{N}_{\mathcal{B}_i}^T} \ldots\right) \middle| \left(\lambda_T^{CPS} \cdot c_{\mathbb{N}_{\mathcal{B}_i}^T}\right) \right\}, \\ \quad \text{if } c_{\mathbb{N}_{\mathcal{B}_i}^T} < \mathfrak{U}^*_{\mathbb{N}_{\mathcal{B}_i}^T}. \\ \left\{ \mathfrak{U}^*_{\mathbb{N}_{\mathcal{B}_i}^T} = \left(\ldots \mathfrak{U}^*_{D_l^{\mathcal{B}_i,T} \in \mathbb{N}_{\mathcal{B}_i}^T} \ldots\right) \middle| \left(\lambda_T \cdot \mathfrak{U}^*_{\mathbb{N}_{\mathcal{B}_i}^T}\right) \right\}, \\ \quad \text{otherwise.} \end{cases} \\ &\text{s.t., } \begin{cases} \lambda_T^{CPS} = \mathbf{max}\left\{ t \in (0,1] \middle| \sum\nolimits_{D_l^{\mathcal{B}_i,T} \in \mathbb{N}_{\mathcal{B}_i}^T} \mathcal{S}_l^{\mathcal{B}_i,T} \le \mathcal{S}_T^{\mathcal{B}_i} \right\} \\ \lambda_T = \mathbf{max}\left\{ t \in (0,1] \middle| \sum\nolimits_{D_l^{\mathcal{B}_i,T} \in \mathbb{N}_{\mathcal{B}_i}^T} \mathcal{S}_l^{\mathcal{B}_i,T} \le \mathcal{S}_T^{\mathcal{B}_i} \right\} \end{cases} \end{aligned} \tag{8}$$

where $c_{D_l^{\mathcal{B}_i,T}}$ is the claim of $D_l^{\mathcal{B}_i,T}$; it is given by $\mathfrak{U}_l^{\mathcal{B}_i,T}(\cdot)$ with $\mathcal{S}_l^{\mathcal{B}_i,T} = R_l^{\mathcal{B}_i,T}$. $\mathfrak{U}^*_{\mathbb{N}_{\mathcal{B}_i}^T}$ is the vector of utopia values for devices in the $\mathbb{N}_{\mathcal{B}_i}^T$, and $\mathfrak{U}^E_{D_l^{\mathcal{B}_i,T}}$ is the utopia value of $D_l^{\mathcal{B}_i,T}$.

D. MAIN STEPS OF PROPOSED SPECTRUM CONTROL ALGORITHM

In this study, we have developed a new spectrum control scheme with wireless network virtualization. To design our proposed scheme, we formulate a novel joint bargaining game model in two-tier spectrum control processes. Especially, game players work together to make control decisions, and bargain with each other to get mutual advantages. By adopting the main concepts of *WKSBS*, *CPS*, *TPS* and *RTPS*, multiple IoT devices can share fair-efficiently the limited spectrum resources. Based on the interactive bargaining approach, different bargaining solutions are interdependent to strike the appropriate performance balance of UDN system platform. The main steps of the proposed spectrum control algorithm are as follows:

Step 1: For our simulation model, the values of the system parameters and control factors are listed in Table 1, and the simulation scenario is presented in Section IV.

Step 2: Individual IoT devices generate application services such as PSs, SSs, and TSs. To support different traffic services, the $\mathcal{M}_P$, $\mathcal{M}_S$ and $\mathcal{M}_T$ operators work together at the first-tier process and work independently at the second-tier process.

Step 3: At the first-tier, the game $\mathbb{G}_{\mathcal{B}_i}$ is operated to share the $\mathfrak{M}_{\mathcal{B}}$. By using (1), the players' utility functions are defined, and the concept of *WKSBS* is adopted for the $\mathbb{G}_{\mathcal{B}_i}$. Therefore, the values of $\mathcal{S}_P$, $\mathcal{S}_S$ and $\mathcal{S}_T$ slices are decided according to (2).

Step 4: At the second-tier, the $\mathbb{G}_{\mathcal{B}_i}^{\mathcal{M}_P}$, $\mathbb{G}_{\mathcal{B}_i}^{\mathcal{M}_S}$, and $\mathbb{G}_{\mathcal{B}_i}^{\mathcal{M}_T}$ games are operated in parallel to support the PSs, SSs, and TSs. Each game has its own game solution based on the different traffic service characteristics.

Step 5: In the $\mathbb{G}_{\mathcal{B}_i}^{\mathcal{M}_P}$, the $\mathcal{S}_P$ is scheduled for the devices in the $\mathbb{N}_{\mathcal{B}_i}^{P}$. By using (3), the devices' utility functions are defined, and the concept of *CPS* is adopted for the $\mathbb{G}_{\mathcal{B}_i}^{\mathcal{M}_P}$. Therefore, the $\mathcal{S}_P$ distribution is executed according to (4).

Step 6: In the $\mathbb{G}_{\mathcal{B}_i}^{\mathcal{M}_S}$, the $\mathcal{S}_S$ is scheduled for the devices in the $\mathbb{N}_{\mathcal{B}_i}^{S}$. By using (5), the devices' utility functions are defined, and the concept of *TPS* is adopted for the $\mathbb{G}_{\mathcal{B}_i}^{\mathcal{M}_S}$. Therefore, the $\mathcal{S}_S$ distribution is executed according to (6).

Step 7: In the $\mathbb{G}_{\mathcal{B}_i}^{\mathcal{M}_T}$, the $\mathcal{S}_T$ is scheduled for the devices in the $\mathbb{N}_{\mathcal{B}_i}^{T}$. By using (7), the devices' utility functions are defined, and the concept of *RTPS* is adopted for the $\mathbb{G}_{\mathcal{B}_i}^{\mathcal{M}_T}$. Therefore, the $\mathcal{S}_T$ distribution is executed according to (8).

Step 8: The network operators and agents constantly self-monitor the current UDN situations, and proceed to Step 2 for the next spectrum control process.

IV. PERFORMANCE EVALUATION

In this section, the performance of our proposed algorithm is evaluated through simulations, and is compared with other existing protocols to confirm the superiority of our approach.

A. EXPERIMENTAL METHOD

As mentioned in Section II, we select the *HGRM*, *MVRA* and *MHRA* schemes [2], [4], [10], which are recently published novel spectrum control protocols by applying the WNV technology. The assumptions of our simulation environment are as follows [15]–[17]:

- The simulated UDN system platform consists of 10 BSs $\mathbb{B} = \{\mathcal{B}_1, \mathcal{B}_2, \ldots, \mathcal{B}_{10}\}$.
- There are 300 IoT mobile devices $\mathbb{N} = \{D_1, D_2, \ldots, D_{300}\}$, and they are regularly located in the cell area.
- The process for service request generation is Poisson with rate Λ (services/s), and the range of the offered service load was varied from 0 to 3.0.
- Three type traffic services are assumed based on the different characteristics of services. Each type traffic has different applications according to the connection duration and spectrum requirements.
- The total spectrum capacity of each BS ($\mathfrak{M}_{\mathcal{B}}$) is 100 Gbps.
- To reduce computational complexity, the amount of spectrum allocation is specified in terms of basic spectrum units (BSUs), where one BSU is the minimum amount (e.g., 2.5 Mbps in our system) of spectrum adjustment.

TABLE 1. System parameters used in the simulation experiments.

Parameter	Value	Description
n	10	the number of base stations
χ, σ, η	2.5, 1, 0.5	control parameters for $U_{\mathcal{M}_P}(\cdot)$
ξ, ε, ζ	1, 4, 2	system adjustment factors for $U_{\mathcal{M}_S}(\cdot)$
γ, Δ	2 , 1	control parameters for $U_{\mathcal{M}_T}(\cdot)$
α, δ, θ	2, 1, -1	control parameters for $\mathfrak{U}^{\mathcal{B},P}(\cdot)$
$\phi, \beta, \rho, \omega$	2, 1, -2, 1	control parameters for $\mathfrak{U}^{\mathcal{B},S}(\cdot)$
μ, τ	3, 1	control parameters for $\mathfrak{U}^{\mathcal{B},T}(\cdot)$
$\mathcal{W}_{\mathcal{M}_P}$	0.5	bargaining weight for $\mathcal{M}_P$ in *WKSBS*
$\mathcal{W}_{\mathcal{M}_S}$	0.3	bargaining weight for $\mathcal{M}_S$ in *WKSBS*
$\mathcal{W}_{\mathcal{M}_T}$	0.2	bargaining weight for $\mathcal{M}_T$ in *WKSBS*

Type	Spectrum Claim (c)	Truncated Claim ($\hat{c}$)	Connection Duration (average/s)
PSs	15 Mbps	N/A	120 sec (2 min)
	10 Mbps	N/A	60 sec (1 min)
SSs	25 Mbps	20 Mbps	30 sec (0.5 min)
	20 Mbps	15 Mbps	60 sec (1 min)
TSs	35 Mbps	N/A	45 sec (0.75 min)
	30 Mbps	N/A	90 sec (1.5 min)

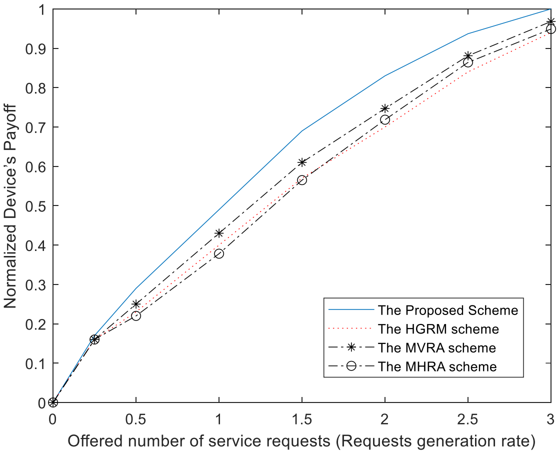

FIGURE 2. Normalized device's payoff in the UDN system.

- To calculate the bargaining solutions, the utility of the disagreement point, i.e., d, is zero in our system where $d = \{0_N\}$.
- For the *WKSBS*, weights for MVNOs are defined as 0.5, 0.3 and 0.2, respectively, where $\mathcal{W}_{\mathcal{M}} = \left(\mathcal{W}_{\mathcal{M}_P}, \mathcal{W}_{\mathcal{M}_S}, \mathcal{W}_{\mathcal{M}_T}\right)$ (0.5, 0.3, 0.2).
- The system performance measures obtained based on 100 simulation runs are plotted as a function of the offered service request load.
- The performance measures obtained are the normalized payoff of device, system throughput, and fairness among devices in the UDN system.
- For simplicity, we assume the absence of physical obstacles in wireless communications.

B. SIMULATION RESULTS WITH NUMERICAL ANALYSIS

Fig. 2 shows a performance comparison of the device's payoff in our scheme and the existing *HGRM*, *MVRA* and *MHRA* schemes. In this simulation model, the payoff of the device

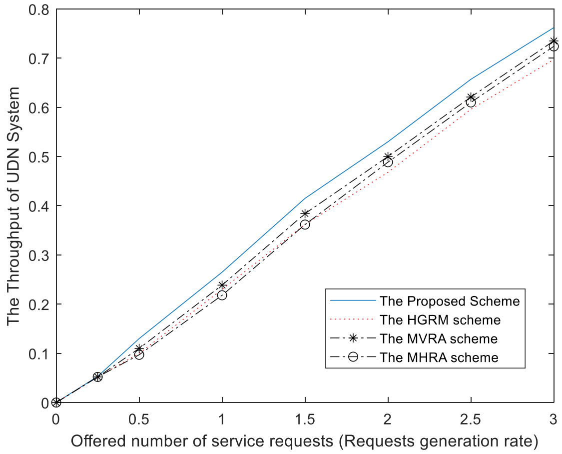

FIGURE 3. **Throughput of UDN system infrastructure.**

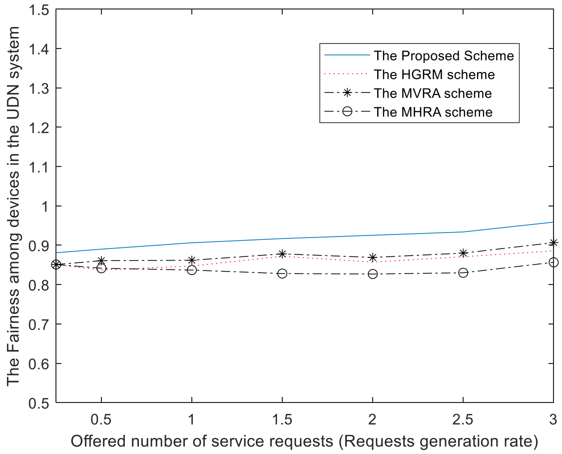

FIGURE 4. **The Fairness among devices in the UDN system.**

is normalized for a fair comparison. This performance criterion is very important from the viewpoint of end users. It is strongly related to user's satisfaction and service quality. In Fig. 2, we can see the performance trend under different service request rates. Under low to heavy traffic load distributions, our joint-bargaining approach can effectively share limited BS spectrum resource. This can lead to a higher device payoff, resulting in a greater service satisfaction. This is a significant advantage for end users.

Fig. 3 shows the system throughput of the UDN infrastructure for the different schemes. In our simulation model, the throughput is the ratio of the traffic service that is successfully completed to all the requested applications. Because the system throughput is strongly associated with the summation of the payoff of each device, the performance trend shown in Fig. 3 is very similar to the curves in Fig. 2. Under different service request intensities, our proposed scheme mediates different bargaining solution ideas to effectively handle the different type traffic services. Therefore, our approach is comparatively better than the existing protocols while adaptively responding to the current UDN system situations; this is what it has come to.

Fig. 4 plots the fairness among devices in the UDN system. This fairness index represents how to share the limited spectrum resource in the viewpoint of social welfare. Our two-tier bargaining model effectively compromises the contrasting viewpoints of the $\mathcal{M}_P$, $\mathcal{M}_S$ and $\mathcal{M}_T$ operators, and provides the most proper combination of the different fair issues among different bargaining solutions. Therefore, under diversified traffic condition changes, our proposed scheme can maintain a higher fairness among devices while efficiently sharing the limited UDN spectrum resource.

V. SUMMARY AND CONCLUSION

Facing with the different type traffic coexisting scenario in the future network, wireless network virtualization will be utilized to slice and share the network resource among different service providers. In this study, we have presented a new UDN spectrum control algorithm, which is designed as a two-tier bargaining game model. By jointly considering the *WKSBS*, *CPS*, *TPS* and *RTPS*, each individual MVNO work together at the first-tier and work independently at the second-tier. Based on different bargaining solutions, our interactive bargaining approach can strike an appropriate performance balance for the UDN system. To confirm the superiority of our approach, we conduct extensive simulations to compare our proposed scheme with existing state-of-the-art *HGRM*, *MVRA* and *MHRA* protocols. The numerical results demonstrate that we can improve the performance of the UDN system in terms of the system throughput, device's payoff and fairness.

In future work, we can extend our current study in multiple directions. One future direction is to explore the transmission strategy for vehicle network scenarios, and we will consider the congestion problem with traffic prediction techniques. Another potential direction for future research is to investigate the user location issue, which is strongly related to the user mobility. In addition, we will extend this work by incorporating multiple carrier aggregation techniques and developing a more sophisticated spectrum control scheme that can be applied when different carrier aggregations occur.

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COMPETING OF INTERESTS

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

AUTHOR' CONTRIBUTION

The author is a sole author of this work and ES (i.e participated in the design of the study and performed th statistical analysis).

AVAILABILITY OF DATA AND MATERIAL

The data used to support the findings of this study are availabl by contacting the corresponding author HYPERLINK mailto:swkim01@sogang.ac.kr swkim01@sogang.ac.kr.

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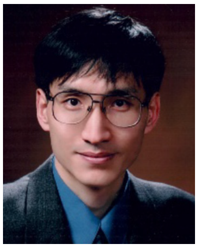

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