IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 30 July 2023, accepted 8 August 2023, date of publication 14 August 2023, date of current version 22 August 2023.

Digital Object Identifier 10.1109/ACCESS.2023.3304632

RESEARCH ARTICLE

Hierarchical Multi-Service Resource Allocation Scheme for Future Wireless Network Virtualization

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This work was supported in part by the Ministry of Science and ICT (MSIT), South Korea, under the Information Technology Research Center (ITRC) Support Program supervised by the Institute for Information & Communications Technology Planning & Evaluation (IITP) under Grant IITP-2023-2018-0-01799; and in part by the Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education under Grant 2021R1F1A1045472.

ABSTRACT Future network is envisioned to be a multi-service network which can support more than one distinct communications service type over the same physical infrastructure. As a potential game changer, wireless network virtualization (WNV) allows the coexistence of multiple network slices over a shared physical platform. One key advantage of WNV is to effectively support multiple traffic types in a multi-service network. In this paper, we propose a novel resource allocation scheme for future wireless networks. Our proposed scheme is formulated as a joint control paradigm, which consists of upper and lower control stages. In the upper control stage, the ideas of *Kalai and Smorodinsky bargaining solution* (*KSBS*) and *Banzhaf value* (*BV*) are combined to allocate the resource to virtual networks. In the lower control stage, each virtual network operator distributes its assigned resource into corresponding mobile devices based on the multi-criteria bargaining solution, which combines the *Nash bargaining solution* (*NBS*) and *KSBS* to optimize the overall performance subject to different service requirements. To effectively share the limited physical resource, each stage control mechanism works together in an interactive manner. The main novelty of our approach is to reach a reciprocal consensus among competitive network agents. Through system simulations, numerical results show the superiority of our proposed control approach. Especially, the proposed scheme increases the system throughput, device payoff, and fairness by about 10%, 10% and 15%, respectively, in comparison with existing state-of-the-art WNV protocols. Finally, we highlight interesting research challenges and point out potential directions to spur further research in this promising research area.

INDEX TERMS Wireless network virtualization, Kalai and Smorodinsky bargaining solution, nash bargaining solution, multi-criteria bargaining solution, Banzhaf value.

I. INTRODUCTION

Recently, the Internet-based applications generate a huge amount of data to provide us with the rich knowledge and information. With the emergence of various mobile multimedia applications, the requirements for network capacity and service quality are getting higher. To meet these extreme demands, fifth-generation (5G) wireless network is regarded as the essential infrastructure to offer high speed, low latency, and massive connection services. To cater such an overwhelming increase of mobile data traffic, 5G networks are expected to be equipped with 5 times as many as base stations (BSs) and utilize 200 times more spectrum resource than 4G networks. This makes the orchestration of so many 5G network agents to achieve the desired goals get even more challenging than before. To promote the technology, standardization and industrialization of 5G networks, the extensive research activities have emerged in both the academic and industrial communities [1], [2].

The main objective of upcoming 5G wireless networks focuses on the enabling mechanisms to ensure wireless multimedia services at any time and any place, and in any manner. However, these services, which are bandwidth-intensive and time-sensitive over the emerging 5G wireless networks, are

The associate editor coordinating the review of this manuscript and approving it for publication was Miguel López-Benítez.

constrained from the limited wireless resources; it imposes many new challenging problems not encountered in the 4G networks. Nowadays, wireless network virtualization (WNV) has been proposed as a promising candidate to solve the contradiction between the limited resources and the increasing demands of wireless multimedia services by isolating and sharing network resources among different slices. Usually, virtualization refers to the creation of a set of logical infrastructure using a given set of physical entities, but in a manner that is transparent to end users. It can provide a new opportunity to effectively improve the key resource utilization by creating virtual versions of corresponding physical resources [3], [4], [5].

The WNV technology decouples the role of traditional network operator into two logical roles: the infrastructure provider (InP) and the virtual network operators (VNOs). An InP owns the physical network infrastructures, such as multiple BSs, antennas, and backhaul, and the associated wireless resources such as radio spectrum. From the InP, multiple VNOs can lease these resources, and provide them to the corresponding users by creating their own virtual networks. Simply, we can see the WNV technology as an effective way to mitigate capital and operational expenditures for the InP while sharing the physical spectrum resource for multiple VNOs. Even though the WNV is considered as a promising technology for the 5G networks, it faces a difficult control problem - how to share the virtualized resource for multiple VNOs, which must fulfill the dynamic demands of multiple services. This problem becomes more challenging in a scenario where individual VNOs behave selfish without considering the desired social efficiency [4], [6].

With the diverse wireless service types, the quality of service (QoS) requirements are diverse. According to the ITU Radio communication sector, there are three generic usage scenarios such as Ultra Reliable and Low Latency Communications (URLLC), enhance mobile broadband (eMBB), and massive machine type communication (mMTC). Especially, the URLLC focuses on latency-sensitive applications for self-driving and drone control services. The eMBB concerns high data rate services like as high definition videos and virtual reality. The mMTC has high requirements for connection density for smart city and smart home. An important approach to wireless network virtualization is to create a resource pool by combining the InP resource and create logical partitions, which are called slices, based on the QoS requirements of different services. Simply, a slice is a virtual network; it is just like a slice of the substrate network. Therefore, multiple services, which are executed with slices, are decoupled from the underlying physical network. This approach enables efficient resource sharing among heterogeneous services while fully maximizing the potential of virtualization [4], [7].

Usually, network virtualization works only aimed at the user-level resource slicing while ignoring the resource isolation in the service-level allocation. To solve conflicts in the multi-service wireless network, service-level and user-level requirements should be taken into account for the resource allocation problem. Therefore, it is necessary to develop a two-level resource allocation scheme, which splits the resource allocation process into two stages: inter-slice allocation stage and intra-slice allocation stage. Due to the time-varying property of each data traffic services, two resource allocation processes dynamically interact with each other based on the online manner [4].

To implement the two-level resource allocation scheme, joint control paradigm is vitally important to maximize the performance gains obtainable from the spectrum sharing process. Traditionally, joint control is the contractually agreed sharing of control of an arrangement, which exists only when decisions about the relevant activities require the unanimous consent of the parties sharing control. For the joint control paradigm, cooperative optimization is inspired by the principle of coordination work, which is a newly discovered general optimization method for attacking hard optimization problems. As a branch of cooperative optimization, cooperative game theory was introduced. At the 1950, the first cooperative game solution was proposed by J. Nash, namely, *Nash bargaining solution* (*NBS*), in his pioneering paper. Since then,a number of cooperative game solutions have been proposed by redeeming his original idea [4], [8].

In cooperative games, game players take joint actions so as to realize their goals. However, the players are not assumed to be altruistic; they only join a coalition if this helps them increase their individual profit. Therefore, the main interest in cooperative games is to fairly distribute the outcome to each player according to their contributions. In this paper, we aim to design a novel joint control scheme for the inter and intra slice allocation processes. Based on the hierarchical cooperative game model, we address two control issues; i) how to share the spectrum resource in the inter-slice allocation process, and ii) how to allocate the assigned spectrum resource in the intra-slice allocation process. From the perspective of cooperation, network agents diffuse information to obtain a globally optimal solution in the 5G multi-service network [8].

The rest of the paper is organized as follows. We describe the basic ideas of cooperative games and summarize the major contributions of this study in Section II. Section III reviews the state-of-the art research papers on resource allocation protocols for wireless network virtualization. Section IV presents the system infrastructure and problem formulation. And then, the bargaining and value solution concepts are explained in detail. They are adopted in our joint control paradigm. Finally, the primary steps of our two-level game model are provided. Simulation results and performance analysis are described in Section V. In this section, the settings for the numerical analysis are also presented and discussed. Finally, we present our concluding remarks and future work in Section VI.

II. TECHNICAL CONCEPTS AND MAIN CONTRIBUTIONS

Cooperative game situation is usually described by the set of all possible outcomes or payoff vectors that the players can obtain through agreement, and status quo point which is the result obtainable if the players fail to reach an agreement.

In this game, several players aim to share a surplus that they are able to generate through cooperation. Therefore, the major goal of cooperative games is that players agree on how the surplus should be split. Two different approaches to solve cooperative games can be found in the literature; one is bargaining approach and the other is value approach. In 1950, J. Nash first proposed the *NBS* as a simple cooperative game solution. It predicts an outcome based only on information about each player's preferences. His bargaining game model is formulated by an expected utility function over the set of feasible agreements and the outcome which would result in case of disagreement [8].

Another relevant bargaining solution that has to be taken into account in cooperative environments is the *Kalai and Smorodinsky bargaining solution*(*KSBS*). By anchoring on the utopia point, which is the maximal aspirations for all players, the *KSBS* is the intersection point between the bargaining set and the line from utopia point to the status quo point. Both the *NBS* and *KSBS* aim to recommend feasible results which can be accepted by all agents on the basis of several rationality principles. They provide several axiomatic characterizations with different properties. Recently, the multi-criteria cooperative game is concerned with situations in which a number of players must take into account several criteria; each of which depends on the decision of all players. As a generalization of classic cooperative games, the multi-criteria cooperative game is useful to support the evaluation, selection and ranking criteria and alternatives to aid game players in making a decision. However, until now, the study on multi-criteria bargaining solutions is scarce [8], [9].

Banzhaf value(*BV*) is a new solution concept for cooperative games. It is looking for a fair allocation of collectively gained profits between cooperating players. In the value based approach, any subset of players is assumed to be free to form a coalition. Therefore, a value solution concept may be viewed as a real-valued function defined on the collection of all subsets of players. Simply, we can think that the *BV* is the probabilistic value when coalitions not containing a player are equally to arise. As is well known, the *BV* is useful especially for analyses of voting situations. In this study, we aim to optimize the performance of virtualized multi-service wireless networks. Based on the *NBS*, *KSBS* and *BV*, our proposed scheme is designed as a joint control paradigm in an interactive fashion. In the proposed scheme, the upper and lower control stages are sophisticatedly combined, and work together to achieve a socially optimal solution. The significant major contributions of our study are summarized as follows [10];

- To maximize the system performance for the virtualized multi-service network platform, we design a hierarchical cooperative game model based on the *NBS*, *KSBS* and *BV*. To the best of our knowledge, our joint control paradigm based on cooperative game theory is the first in the literature for the 5G network virtualization scenario.
- To allocate the spectrum resource in the upper level stage, we formulate the inter-slice allocation process, and select best strategies based on the combination of *KSBS* and *BV*.
- To distribute the assigned spectrum resource in the lower level stage, we implement the intra-slice allocation process according to the multi-criteria cooperative game model. For different criteria, the *NBS* and *KSBS* are combined to get a compromised solution.
- In our joint control paradigm, upper and lower control stages are jointly combined, and work together to effectively share the limited spectrum resource in the virtualized network platform. With the cooperative game solutions, our approach explores the sequential interactions between network agents, and obtains reciprocal advantages for the excellent system performance.
- Simulations are implemented to analyze the performance of proposed algorithms. Numerical results show that our approach is more suitable for multi-service network platform compared with the existing state-of-the-art virtualization control protocols.

III. RELATED WORK

In recent years, a number of protocols have been proposed to enable virtualization in 5G networks. In this section, we touch on currently published state-of-the-art papers relevant to the research topic of our study. In [4], Y. Han proposed the *Resource Allocation for Multi-Service Virtualization* (*RAMSV*) scheme for hierarchical wireless networks. Based on three 5G generic scenarios, the *RAMSV* scheme decomposes the resource slicing problem into sub-problems; the inter-slice and intra-slice resource allocation processes. First, the inter-slice process is conducted by modeling the packets arriving and serving model in a coarse-grained manner. For the spectrum pre-allocation among slices, this process is formulated as a multi-objective optimization problem. Second, the intra-slice process is formulated as a stochastic optimization problem in a fine-grained manner. By considering dynamic traffic arrivals and channel conditions, this process is transformed into a delay-aware optimization problem, which is solved by a distributed heuristic algorithm. Extensive simulations are conducted to study the performance evaluation, and numerical results validate that the *RAMSV* scheme has a good performance close to the optimal solution with a lower complexity [4].

The paper [7] developed the *Multi-Service Virtualized Resource Allocation* (*MSVRA*) scheme for future wireless networks. Usually, the virtualized resource allocation problem for multi-services is a very difficult optimization problem; it should not only optimize the performance but also satisfy various QoS requirements. To reduce the problem complexity, the *MSVRA* scheme decouples the resource allocation problem into two simpler control mechanisms such as inter-slice and intra-slice resource scheduling mechanisms. For the inter-slice mechanism, a discrete optimization problem is designed, and a sub-optimal solution is obtained by using a heuristic algorithm. For the intra-slice mechanism, novel scheduling algorithms are developed for

TABLE 1. Thee notations for abbreviations, symbols, and parameters.

Acronym	Explanations
WNV	wireless network virtualization
KSBS	*Kalai and Smorodinsky bargaining solution*
BV	*Banzhaf value*
NBS	*Nash bargaining solution*
BSs	base stations
InP	infrastructure provider
VNOs	virtual network operators
QoS	quality of service
URLLC	Ultra Reliable and Low Latency Communications
eMBB	enhance mobile broadband
mMTC	massive machine type communication
RAMSV	*Resource Allocation for Multi-Service Virtualization*
MSVRA	*Multi-Service Virtualized Resource Allocation*
MDSRA	*Market-Driven Stochastic Resource Allocation*
Notations	**Explanations**
$\mathbb{B}$	a set of BSs
$\mathbb{D}$	a set of mobile devices
$\mathcal{V}_I, \mathcal{V}_{II}, \mathcal{V}_{III}$	VNOs for Type-I, II, III services, respectively.
$\mathcal{S}_I, \mathcal{S}_{II}, \mathcal{S}_{III}$	network slices for Type-I, II, III services, respectively.
$\mathfrak{M}_{\mathcal{B}}^{I}, \mathfrak{M}_{\mathcal{B}}^{II}, \mathfrak{M}_{\mathcal{B}}^{III}$	the amounts of allocated resources for Type-I, II, III services, respectively.
$\mathbb{G}_{\mathcal{V}}^{\mathcal{B}}$	the upper level cooperative game
$\mathbb{G}_{\mathcal{D}}^{\mathcal{V}}$	the lower level cooperative game
$\mathfrak{M}_{\mathcal{B}}$	the total spectrum amount of $\mathcal{B}$
$\mathfrak{M}_{\mathcal{B}}^{X}$	an allocated spectrum amount for the $\mathcal{V}_X$
$U_{\mathcal{V}}(\cdot)$	the strategy and utility function of $\mathcal{V}$
$\Upsilon_{\mathcal{D}}$	the spectrum resource of each device
$\mathfrak{U}_{\mathcal{D}}(\cdot)$	the utility function of each device
d	disagreement point
S	the set of all feasible outcomes
$\mathfrak{R}_{\mathcal{B}}$	the equity base amount of spectrum resource
$\delta, \mu, \eta, \varrho, \varepsilon$	adjustment parameters for the $U_{\mathcal{V}}(\cdot)$
$\mathfrak{U}_{\mathcal{D}}^{T}(\cdot), \mathfrak{U}_{\mathcal{D}}^{Q}(\cdot)$	two sub-functions of $\mathfrak{U}_{\mathcal{D}}(\cdot)$
β, θ	control parameters for the function $\mathfrak{U}_{\mathcal{D}}^{T}(\cdot)$
ξ, κ	control parameters for the function $\mathfrak{U}_{\mathcal{D}}^{Q}(\cdot)$
$\mathfrak{U}_{\mathcal{D}}^{*}(\cdot)$	the $\mathcal{D}$'s ideal outcome
$d_{\mathcal{D}}$	the $\mathcal{D}$'s disagreement point

several specific multi-services. In these mechanisms, utility functions are designed to represent the slice's satisfaction degree. Simulations are implemented to analyze the system performance, and numerical results show that the *MSVRA* scheme is more suitable for specific services compared with the existing protocols [7].

Authors in [11] introduced the *Market-Driven Stochastic Resource Allocation* (*MDSRA*) scheme for wireless network virtualization. In this scheme, there are three main entities, i.e., resource owners, resource buyers, and a resource aggregator. By comprising multiple resource owners and resource buyers, a robust virtualized network architecture is defined. And then, a matching game model is implemented to pair resource buyers with existing resource aggregators according to their particular trading preferences. In this matching game model, technical and nontechnical parameters are considered in the resource selection process. To handle optimization under uncertainty, a chance-constrained stochastic program is adopted for the virtual resource allocation. It can maximize the utilization of the resources while satisfying the resource buyer demands. Finally, simulation results show that the *MDSRA* scheme has good performance with reasonable computational complexity, and affordable network overhead [11].

As discussed above, the earlier schemes in [4], [7], and [11] have been studied on the resource allocation problem for 5G virtualized wireless networks. Although these studies tackled the same control issues, which we concern in this study, they did not consider a joint control paradigm based on the cooperative game theory. Unlike the aforementioned the *RAMSV*, *MSVRA* and *MDSRA* schemes, our proposed scheme concerns the combination of different cooperative game solutions for controlling the activities of VNOs and mobile devices, and guides them toward a fair-efficient outcome in the wireless network virtualization.

IV. PROPOSED RESOURCE ALLOCATION SCHEME FOR NETWORK VIRTUALIZATION

This section introduces the multi-service network platform with the WNV technology that we focus on. Then, we explain the basic ideas of *NBS*, *KSBS* and *BV*, which are adopted to design our hierarchical joint control game. After that, our proposed resource allocation algorithm is described strategically in the nine-step procedures.

A. NETWORK VIRTUALIZATION INFRASTRUCTURE AND COOPERATIVE GAME MODELS

In the network virtualization environment, infrastructures are decoupled from the services it provides. As a result,the network operator is decoupled into InP and VNO in wireless virtualization. Specifically, the InP owns the network infrastructure and spectrum resource, and the VNO realizes virtualization while i) allocating the physical resource to each virtual network, and ii) scheduling multiple application services. In this study, we assume a virtualized wireless network with a single InP that has a set of BSs denoted by $\mathbb{B} = \{\mathcal{B}_1, \ldots, \mathcal{B}_n\}$. In each BS, there are three VNOs ($\mathcal{V}_I$, $\mathcal{V}_{II}, \mathcal{V}_{III}$) for three slice types; they are Type-I slice ($\mathcal{S}_I$) for the URLLC network, Type-II slice ($\mathcal{S}_{II}$) for the eMBB network, and Type-III slice ($\mathcal{S}_{III}$) for the mMTC network. Mobile devices $\mathbb{D} = \{\mathcal{D}_1, \ldots, \mathcal{D}_m\}$ are randomly distributed in the network area while connected to their corresponding BSs. Each individual BS carries out the spectrum resource management, scheduling, admit control,

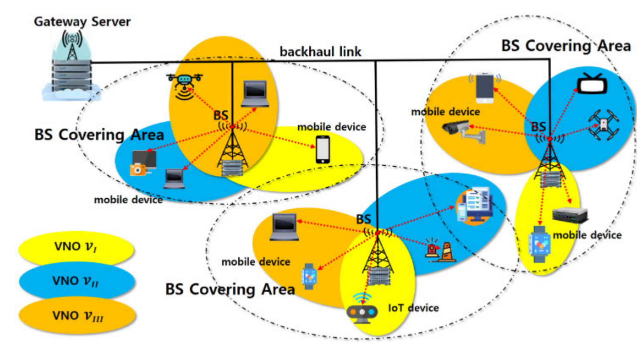


FIGURE 1. A general platform in the multi-service network virtualization.

and more functionalities for their corresponding devices. As shown in Fig. 1, we assume that each BS is virtualized and sliced into three isolated slices, and we summarize the notations used in this paper in Table 1 [4], [7].

In our proposed scheme, we assume that each BS and spectrum resource are owned and managed by a single InP which provides its network infrastructure as a service to VNOs. In each BS, the resource allocation is performed in the two-level stages. In the upper level stage, the BS estimates service demands from all slices and its resource is orthogonally divided into three parts for each type slice; it is called the inter-slice resource allocation where $\mathfrak{M}_{\mathcal{B}}^{I}$, $\mathfrak{M}_{\mathcal{B}}^{II}$ and $\mathfrak{M}_{\mathcal{B}}^{III}$ are the amounts of allocated resources for the Type-I, Type-II and Type-III slices, respectively. In the lower level stage, the $\mathcal{V}_I$, $\mathcal{V}_{II}$, and $\mathcal{V}_{III}$ distribute the assigned $\mathfrak{M}_{\mathcal{B}}^{I}$, $\mathfrak{M}_{\mathcal{B}}^{II}$ and $\mathfrak{M}_{\mathcal{B}}^{III}$ resources into their corresponding devices; it is called the intra-slice resource allocation [4], [7].

In this paper, we develop two cooperative games in the upper and lower level stages; they are hierarchically organized based on the joint control paradigm, and work together to achieve reciprocal advantages. The upper level cooperative game $\left(\mathbb{G}_{\mathcal{V}}^{\mathcal{B}}\right)$ allocates the spectrum resource for VNOs, and the lower level cooperative game $\left(\mathbb{G}_{\mathcal{D}}^{\mathcal{V}}\right)$ distributes the allocated resource into corresponding mobile devices. Through the $\mathbb{G}_{\mathcal{V}}^{\mathcal{B}}$ and $\mathbb{G}_{\mathcal{D}}^{\mathcal{V}}$ games, the InP, VNOs and devices are interactively associated with each other in an coordinated manner. Therefore, a mutually acceptable solution is obtained for different network agents. Formally, we define the tuple entities in our proposed $\mathbb{G}_{\mathcal{V}}^{\mathcal{B}}$ and $\mathbb{G}_{\mathcal{D}}^{\mathcal{V}}$ game models, such as

$$\begin{aligned}
&\mathbb{G}\\
&=\left\{\mathbb{G}_{\mathcal{V}}^{\mathcal{B}},\ \mathbb{G}_{\mathcal{D}}^{\mathcal{V}}\right\}\\
&=\left\{\begin{matrix}\mathbb{B},\left(\mathcal{V}_I,\ \mathcal{V}_{II},\mathcal{V}_{III}\right),\mathbb{D},\\ \mathbb{G}_{\mathcal{V}}^{\mathcal{B}}=\left\{X\in\{I,II,III\}\,|\mathfrak{M}_{\mathcal{B}},\mathcal{V}_X,\mathfrak{M}_{\mathcal{B}}^{X},U_{\mathcal{V}_X}(\cdot)\right\},\\ \mathbb{G}_{\mathcal{D}}^{\mathcal{V}}=\left\{\mathbb{G}_{\mathcal{D}}^{\mathcal{V}_{X\in\{I,II,III\}}},\mathfrak{M}_{\mathcal{B}}^{X}|\mathbb{D}_{\mathcal{V}_X},\gamma_{\mathcal{D}},\mathfrak{U}_{\mathcal{D}}(\cdot)\right\},\\ T\end{matrix}\right\}.
\end{aligned}$$

- $\mathbb{B}$ and $\mathbb{D}$ represent the sets of BSs, and mobile devices, and the $\mathcal{V}_I$, $\mathcal{V}_{II}$ and $\mathcal{V}_{III}$ are the VNOs of the URLLC, eMBB, and mMTC networks,respectively.
- In the upper level game $\mathbb{G}_{\mathcal{V}}^{\mathcal{B}}$, VNOs are game players, which exist in each $\mathcal{B}$. $\mathfrak{M}_{\mathcal{B}}$ is the total spectrum amount of $\mathcal{B}$, and $\mathfrak{M}_{\mathcal{B}}^{X}$ is an allocated spectrum amount for the $\mathcal{V}_X$ where $\mathfrak{M}_{\mathcal{B}}=\bigcup_{X\in\{I,II,III\}}\mathfrak{M}_{\mathcal{B}}^{X}$.
- In the $\mathbb{G}_{\mathcal{V}}^{\mathcal{B}}$, the $\mathfrak{M}_{\mathcal{B}}^{X}$ and $U_{\mathcal{V}_X}(\cdot)$ are the strategy and utility function of $\mathcal{V}_X$, respectively.
- The lower game $\mathbb{G}_{\mathcal{D}}^{\mathcal{V}}$ consists of three sub-games, such as $\mathbb{G}_{\mathcal{D}}^{\mathcal{V}_I}$, $\mathbb{G}_{\mathcal{D}}^{\mathcal{V}_{II}}$, and $\mathbb{G}_{\mathcal{D}}^{\mathcal{V}_{III}}$, for three type slices. They are operated in a distributed parallel fashion.
- In the $\mathbb{G}_{\mathcal{D}}^{\mathcal{V}}$, the $\mathbb{D}_{\mathcal{V}_I}$, $\mathbb{D}_{\mathcal{V}_I}$ and $\mathbb{D}_{\mathcal{V}_{III}}$ are the corresponding device sets of $\mathcal{V}_I$, $\mathcal{V}_{II}$ and $\mathcal{V}_{III}$, respectively, where $\mathbb{D}=\mathbb{D}_{\mathcal{V}_I}\cup\mathbb{D}_{\mathcal{V}_I}\cup\mathbb{D}_{\mathcal{V}_{III}}$.
- In the $\mathbb{G}_{\mathcal{D}}^{\mathcal{V}_I}$, $\mathbb{G}_{\mathcal{D}}^{\mathcal{V}_{II}}$, and $\mathbb{G}_{\mathcal{D}}^{\mathcal{V}_{III}}$ games, mobile devices in the $\mathbb{D}_{\mathcal{V}_I}$, $\mathbb{D}_{\mathcal{V}_I}$, and $\mathbb{D}_{\mathcal{V}_{III}}$ are game players, and the $\gamma_{\mathcal{D}}$ is assigned spectrum resource of each device. For the $\mathcal{D}_k\in\mathbb{D}_{\mathcal{V}_X}$, the $\gamma_{\mathcal{D}_k}$ and $\mathfrak{U}_{\mathcal{D}_k}(\cdot)$ are its strategy and utility function, respectively, where $\mathfrak{M}_{\mathcal{B}}^{X}=\bigcup_{\mathcal{D}_k\in\mathbb{D}_{\mathcal{V}_X}}\mathfrak{M}_{\mathcal{D}_k}^{X}$.
- Discrete time model $T \in \{t_1,\ldots,t_c,t_{c+1},\ldots\}$ is represented by a sequence of time steps. The length of t_c matches the event time-scale of $\mathbb{G}_{\mathcal{V}}^{\mathcal{B}}$ and $\mathbb{G}_{\mathcal{D}}^{\mathcal{V}}$ games.

B. TECHNICAL CONCEPTS AND IDEAS OF NBS, KSBS AND BV

In this subsection, we quickly review the fundamental concepts of *NBS*, *KSBS* and *BV* for cooperative games.

1) BARGAINING GAME SOLUTIONS FOR COOPERATIVE GAMES

To characterize the basic concept of bargaining solutions, we preliminarily define some mathematical expressions. In a bargaining game, the set $\mathbb{N}=\{1,2,\ldots,n\}$ represents game players, who jointly decide on an agreed-upon point in the set S of all feasible outcomes. The *status quo* or disagreement point d is the result obtainable if the players fail to reach an agreement. Each player $i\in\mathbb{N}$ has his utility function u_i: $S\rightarrow\mathbb{R}$ where $\mathbb{R}$ is the set of real numbers. Intuitively, players attempt to maximize their utility functions. Generally, we assume that there are points in the agreement set that are mutually beneficial to all players. So, all players are incentivized to cooperate. Let $U=\{(u_1(\mathcal{X}),u_2(\mathcal{X}),\ldots,u_n(\mathcal{X}))\,|\mathcal{X}\in S\}$ be the set of the payoffs of all possible agreement points, and $d=\{d_1,d_2,\ldots,d_n\}$. Formally, an $n-$ player cooperative game is described by the pair (S,d) where $S\subseteq\mathbb{R}^n$. Therefore, the major challenge is that which point in the agreement set will be a solution they decide upon [12].

J. Nash gave some axioms to provide the concept of efficiency and fairness for desirable bargaining solutions. If a solution can fulfill his axioms, it is called as the *NBS*, which is a unique and fair Pareto optimal solution. Mathematically, the *NBS* maximizes a product of payoffs [8], [12];

$$\begin{aligned}
\text{NBS}: U=\arg\max_{u_i(\mathcal{X})\in U}\prod_{i=1}^{n}\left(u_i(\mathcal{X})-d_i\right),\\
\text{s.t.},\forall i:\ u_i(\mathcal{X})>d_i
\end{aligned}\qquad(1)$$

The *KSBS* provides a payoff that is proportional to the achievable maximum payoff while ensuring efficiency.

Therefore, each player gets the same fraction of his maximum possible payoff. Geometrically, the *KSBS* is the intersection point between the S and the straight line between the d and the utopia point. This interpretation has considerable intuitive appeal, and makes the *KSBS* an attractive approach in situations where one wishes to balance individual fairness with overall outcome. Mathematically, the *KSBS* is defined as follows [8], [12];

$$KSBS = \max_{u_i(\mathcal{X})\in U}\left\{S\left|\frac{u_1(\mathcal{X})-d_1}{u_1^*-d_1}=\ldots=\frac{u_i(\mathcal{X})-d_2}{u_i^*-d_2}\right.\right.\\ \left.=\ldots=\frac{u_n(\mathcal{X})-d_n}{u_n^*-d_n}\right\} \quad (2)$$

where u_i^* is achieved to allow the player i to occupy all resources, and thus it is his utopia payoff. When the d is zero, the *KSBS* is similar to the weighted balancing problem in a cooperative game (S, d).

2) THE BASIC IDEA OF BANZHAF VALUE

The notion of value is one of the most important solution concepts in cooperative game theory. In the value based approach for cooperative games, a central problem is to define a value, that is a payoff to be given to each player, taking into account his contribution into the cooperative game. Until now, different kinds of value solutions have been introduced. Among them, the *BV* has deserved a lot of attention; its main idea has necessarily the form of a weighted average of the marginal contribution of a given player into coalitions. In the *BV*, the marginal contributions are equally weighted. Therefore, the weights do not depend on the size of the coalition. Generally, a value on $\mathbb{N}$ is a function Φ: $\mathcal{G}\left(2^{\mathbb{N}}\right)\rightarrow\mathbb{R}^n$, which assigns a payoff $\Phi_i(\upsilon)$ to each player $i\in\mathbb{N}$ in a game $\upsilon\in\mathcal{G}\left(2^{\mathbb{N}}\right)$. Mathematically, the *BV* of a player i in a game υ, i.e., $\Phi_i^{\mathbb{N}}(\upsilon)$, is defined as follows [13];

$$\Phi_i^{\mathbb{N}}(\upsilon)=\sum_{T\subseteq\mathbb{N}\backslash i}\left(\frac{1}{2^{n-1}}\times(\upsilon(T\cup i)-\upsilon(T))\right) \quad (3)$$

where T is a possible coalition in the υ, and $\mathbb{N}\backslash i$ means $\mathbb{N}-\{i\}$. Applications of the *BV* are found in many fields, and also have a great appeal into the legal community, because of its intuitive definition. For example, we can assume that a cooperative voting game, which is 0-1 valued, the value 1 indicating that the coalition wins the election. In this context, the *BV* can be interpreted how central a player is for making a coalition winning, called a swing. For counting swings, no weight should be applied; it directly leads to the *BV* [13].

C. THE PROPOSED RESOURCE ALLOCATION SCHEME FOR MULTI-SERVICE NETWORKS

To develop our joint control scheme for multi-service networks, we construct the upper $\left(\mathbb{G}_{\mathcal{V}}^{\mathcal{B}}\right)$ and lower $\left(\mathbb{G}_{\mathcal{D}}^{\mathcal{V}}\right)$ game models. In each BS, the $\mathbb{G}_{\mathcal{V}}^{\mathcal{B}}$ is operated in a distributed manner by the URLLC, eMBB, and mMTC VNOs. For example, the $\mathbb{G}_{\mathcal{V}}^{\mathcal{B}_i}$ is designed by the $\mathcal{B}_i\in\mathbb{B}$ to share the $\mathfrak{M}_{\mathcal{B}_i}$ for its $\mathcal{V}_I$, $\mathcal{V}_{II}$ and $\mathcal{V}_{III}$. In this study, we adopt the *KSBS* for the solution of $\mathbb{G}_{\mathcal{V}}^{\mathcal{B}_i}$. Especially, the *KSBS* has the property of *individual monotonicity*, which means that the increasing of bargaining set (S) in a direction favorable to a specific player always benefits that player. Therefore, the idea of *KSBS* is suitable to share the $\mathfrak{M}_{\mathcal{B}_i}$ for different type services. To get the *KSBS* for the $\mathbb{G}_{\mathcal{V}}^{\mathcal{B}_i}$, we first define the disagree point in the $\mathbb{G}_{\mathcal{V}}^{\mathcal{B}_i}$. For this decision, we employ the concept of *BV*; it is commonly used to measure the bargaining power. The *BV* of $\mathcal{V}_I$, i.e., $\Phi_I^{\mathbb{N}}(\upsilon)$, is calculated as follows;

$$\Phi_I^{\mathbb{N}}(\upsilon)=\sum_{T\subseteq\mathbb{N}\backslash\mathcal{V}_I}\left(\frac{1}{2^{|\mathbb{N}|-1}}\times(\upsilon(T\cup\mathcal{V}_I)-\upsilon(T))\right)\\ \text{s.t., }\mathbb{N}=\{\mathcal{V}_I,\mathcal{V}_{II},\mathcal{V}_{III}\} \quad (4)$$

where $\upsilon(\cdot)$ is estimated based on the bankruptcy allocation method; it is an economic concept where the available resource amount is not sufficient enough to fulfill the demands of all resource claiming agents. In this study, the bankruptcy allocation of $\mathcal{B}_i$ is formulated in a triple $\left(\mathbb{N},\mathfrak{M}_{\mathcal{B}_i},c\right)$ where $c=\left(c_{\mathcal{V}_I},c_{\mathcal{V}_{II}},c_{\mathcal{V}_{III}}\right)$ is a claim vector of VNOsand $0\leq\mathfrak{M}_{\mathcal{B}_i}\leq\sum_{i\in\mathbb{N}}c_i$. The $\upsilon(\cdot):2^{\mathbb{N}}\rightarrow\mathbb{R}$ describes the worth of a coalition $T\subset\mathbb{N}$ can be written as follows [14];

$$\upsilon(T)=\max\left\{\left(\mathfrak{M}_{\mathcal{B}_i}-\sum_{i\in\mathbb{N}\backslash T}c_i\right),0\right\},\quad\text{s.t.,}T\subset\mathbb{N} \quad (5)$$

According to (4)-(5), the $\Phi_I^{\mathbb{N}}(\upsilon)$, $\Phi_{II}^{\mathbb{N}}(\upsilon)$, and $\Phi_{III}^{\mathbb{N}}(\upsilon)$ are obtained in the same manner, and the disagree point of $\mathcal{V}_I$, i.e., $d_{\mathcal{V}_I}$, is calculated as follows.

$$d_{\mathcal{V}_I}=\frac{\Phi_I^{\mathbb{N}}(\upsilon)}{\Phi_I^{\mathbb{N}}(\upsilon)+\Phi_{II}^{\mathbb{N}}(\upsilon)+\Phi_{III}^{\mathbb{N}}(\upsilon)}\times\mathfrak{R}_{\mathcal{B}_i} \quad (6)$$

where $\mathfrak{R}_{\mathcal{B}_i}$ is the equity base amount of spectrum resource. By using (6), $d_{\mathcal{V}_{II}}$ and $d_{\mathcal{V}_{III}}$ are given in the same manner. In the $\mathbb{G}_{\mathcal{V}}^{\mathcal{B}_i}$, the $\mathcal{V}_I$, $\mathcal{V}_{II}$ and $\mathcal{V}_{III}$ are game players, and their utility functions, i.e., $U_{\mathcal{V}_I}(\cdot)$, $U_{\mathcal{V}_I}(\cdot)$, and $U_{\mathcal{V}_I}(\cdot)$, are given as follows;

$$\begin{cases} U_{\mathcal{V}_I}\left(\mathcal{R}_{\mathcal{V}_I},\mathfrak{M}_{\mathcal{B}_i}^I\right)\\ =\left(\exp\left(\dfrac{\min\left(\mathcal{R}_{\mathcal{V}_I},\mathfrak{M}_{\mathcal{B}_i}^I\right)}{\mathcal{R}_{\mathcal{V}_I}}\right)-\delta\right)\times\mathfrak{M}_{\mathcal{B}_i}^I\\ U_{\mathcal{V}_{II}}\left(\mathcal{R}_{\mathcal{V}_{II}},\mathfrak{M}_{\mathcal{B}_i}^{II}\right)\\ =\left(\mu\times\log\left(\eta-\dfrac{\min\left(\mathcal{R}_{\mathcal{V}_{II}},\mathfrak{M}_{\mathcal{B}_i}^{II}\right)}{\mathcal{R}_{\mathcal{V}_{II}}}\right)\right)\times\mathfrak{M}_{\mathcal{B}_i}^{II}\\ U_{\mathcal{V}_{III}}\left(\mathcal{R}_{\mathcal{V}_{III}},\mathfrak{M}_{\mathcal{B}_i}^{III}\right)\\ =\left(\varrho^{\left(\frac{\min\left(\mathcal{R}_{\mathcal{V}_{II}},\mathfrak{M}_{\mathcal{B}_i}^{II}\right)}{\mathcal{R}_{\mathcal{V}_{II}}}\right)}-\varepsilon\right)\times\mathfrak{M}_{\mathcal{B}_i}^{III} \end{cases} \quad (7)$$

where δ is a adjustment parameter for the $U_{\mathcal{V}_I}(\cdot)$, and μ, η are adjustment parameters for the $U_{\mathcal{V}_{II}}(\cdot)$. ϱ and ε are control factors for the $U_{\mathcal{V}_{III}}(\cdot)$. The $\mathcal{R}_{\mathcal{V}_I}$, $\mathcal{R}_{\mathcal{V}_{II}}$ and $\mathcal{R}_{\mathcal{V}_{III}}$ ($or \mathfrak{M}^I_{\mathcal{B}_i}$, $\mathfrak{M}^{II}_{\mathcal{B}_i}$ and $\mathfrak{M}^{III}_{\mathcal{B}_i}$) are the total resource request sums from the $\mathcal{V}_I$, $\mathcal{V}_{II}$ and $\mathcal{V}_{III}$, (*or* the allocated resources for the $\mathcal{V}_I$, $\mathcal{V}_{II}$ and $\mathcal{V}_{III}$), respectively. With the $d_{\mathcal{V}_I}$, $d_{\mathcal{V}_{II}}$ and $d_{\mathcal{V}_{III}}$ values, the *KSBS* for $\mathbb{G}^{\mathcal{B}_i}_{\mathcal{V}}$, i.e., $KSBS^{\mathcal{B}_i}_{\mathcal{V}}\left(\mathfrak{M}_{\mathcal{B}_i}\right)$, is obtained as follows;

$$KSBS^{\mathcal{B}_i}_{\mathcal{V}}\left(\mathfrak{M}_{\mathcal{B}_i}\right) = \max_{\left(\mathfrak{M}^I_{\mathcal{B}_i},\mathfrak{M}^{II}_{\mathcal{B}_i},\mathfrak{M}^{III}_{\mathcal{B}_i}\right)} \left(\begin{array}{l} \frac{U_{\mathcal{V}_I}(\cdot) - d_{\mathcal{V}_I}}{U^*_{\mathcal{V}_I}(\cdot) - d_{\mathcal{V}_I}} \\ = \frac{U_{\mathcal{V}_{II}}(\cdot) - d_{\mathcal{V}_{II}}}{U^*_{\mathcal{V}_{II}}(\cdot) - d_{\mathcal{V}_{II}}} \\ = \frac{U_{\mathcal{V}_{III}}(\cdot) - d_{\mathcal{V}_{III}}}{U^*_{\mathcal{V}_{III}}(\cdot) - d_{\mathcal{V}_{III}}} \end{array} \right)$$
$$\text{s.t. }, \sum_{X\in\{I,II,III\}} \mathfrak{M}^X_{\mathcal{B}_i} \le \mathfrak{M}_{\mathcal{B}_i} \quad (8)$$

where $U^*_{\mathcal{V}_I}(\cdot)$ is the maximized payoff for the $\mathcal{V}_I$, and thus it is his ideal payoff. According to (8), the $\mathfrak{M}^I_{\mathcal{B}_i}$, $\mathfrak{M}^{II}_{\mathcal{B}_i}$, and $\mathfrak{M}^{III}_{\mathcal{B}_i}$ are obtained. Based on these values, the intra-slice allocation process is executed in the lower level stage. Individually, the $\mathcal{V}_I$, $\mathcal{V}_{II}$ and $\mathcal{V}_{III}$ operate their $\mathbb{G}^{\mathcal{V}_I}_{\mathcal{D}}$, $\mathbb{G}^{\mathcal{V}_I}_{\mathcal{D}}$, and $\mathbb{G}^{\mathcal{V}_I}_{\mathcal{D}}$ games, respectively, in a distributed parallel fashion. In the $\mathbb{G}^{\mathcal{V}_I}_{\mathcal{D}}$ game, the $\mathcal{V}_I$'s corresponding devices in the $\mathbb{D}_{\mathcal{V}_I}$ are game players. In the viewpoint of individual devices, there are two performance criteria. One is the throughput based measure, and the other is QoS based measure. Therefore, the utility function of $\mathcal{D}_j \in \mathbb{D}_{\mathcal{V}_I}$, i.e., $\mathfrak{U}_{\mathcal{D}_j}(\cdot)$, consists of two sub-functions where $\mathfrak{U}_{\mathcal{D}_j}(\cdot) = \left\{\mathfrak{U}^T_{\mathcal{D}_j}(\cdot), \mathfrak{U}^Q_{\mathcal{D}_j}(\cdot)\right\}$. They are given as follows;

$$\mathfrak{U}_{\mathcal{D}_j}\left(\mathfrak{U}^T_{\mathcal{D}_j}, \mathfrak{U}^Q_{\mathcal{D}_j} | \mathfrak{M}^I_{\mathcal{B}_i}, \mathcal{R}_{\mathcal{D}_j}, \gamma_{\mathcal{D}_j}\right) = \begin{cases} \mathfrak{U}^T_{\mathcal{D}_j}\left(\mathfrak{M}^I_{\mathcal{B}_i}, \mathcal{R}_{\mathcal{D}_j}, \gamma_{\mathcal{D}_j}\right) \\ = \left[\beta \times \left(\frac{1}{1+\exp\left(-\frac{\min\left(\mathcal{R}_{\mathcal{D}_j}, \gamma_{\mathcal{D}_j}\right)}{\mathcal{R}_{\mathcal{D}_j}}\right)} - \theta\right)\right] \times \gamma_{\mathcal{D}_j} \\ \mathfrak{U}^Q_{\mathcal{D}_j}\left(\mathfrak{M}^I_{\mathcal{B}_i}, \mathcal{R}_{\mathcal{D}_j}, \gamma_{\mathcal{D}_j}\right) \\ = \left[\xi - \exp\left(\kappa \times \frac{\min\left(\mathcal{R}_{\mathcal{D}_j}, \gamma_{\mathcal{D}_j}\right)}{\mathcal{R}_{\mathcal{D}_j}}\right)\right] \times \gamma_{\mathcal{D}_j} \end{cases}$$
$$\text{s.t. }, \sum_{\mathcal{D}_k\in\mathbb{D}_{\mathcal{V}_I}} \gamma_{\mathcal{D}_k} \le \mathfrak{M}^I_{\mathcal{B}_i} \quad (9)$$

where β, θ are control parameters for the throughput based function $\mathfrak{U}^T_{\mathcal{D}_j}(\cdot)$, and ξ, κ are control parameters for the QoS based function $\mathfrak{U}^Q_{\mathcal{D}_j}(\cdot)$. $\mathcal{R}_{\mathcal{D}_j}$ is the requested resource amount from the $\mathcal{D}_j$, and $\gamma_{\mathcal{D}_j}$ is the allocated resource for the $\mathcal{D}_j$. In the $\mathbb{G}^{\mathcal{V}_I}_{\mathcal{D}}$, the assigned $\mathfrak{M}^I_{\mathcal{B}_i}$ is distributed for the devices in the $\mathbb{D}_{\mathcal{V}_I}$. To implement this intra-slice allocation process, we develop a new multi-criteria cooperative game based on the of *NBS* and *KSBS*. By considering two different criteria, the multi-criteria solution for the $\mathbb{G}^{\mathcal{V}_I}_{\mathcal{D}}$, i.e., $MCS\left(\mathbb{G}^{\mathcal{V}_I}_{\mathcal{D}}\right)$, is obtained as follows (10), shown at the bottom of the next page, where $\mathfrak{U}^*_{\mathcal{D}_j}(\cdot)$ is the $\mathcal{D}_j$'s ideal outcome, and $d_{\mathcal{D}_j}$ is his disagreement point. The $\gamma^T_{\mathcal{D}_j}$, $\gamma^Q_{\mathcal{D}_j}$ are obtained by maximizing $\mathcal{S}^T$ and $\mathcal{S}^Q$, respectively. Based on the $\gamma^T_{\mathcal{D}_j}$, $\gamma^Q_{\mathcal{D}_j}$ values, the finally allocated resource for the $\mathcal{D}_j$, i.e., $\Gamma_{\mathcal{D}_j}$, is decided as follows;

$$\Gamma_{\mathcal{D}_j} = \frac{\Upsilon^*_{\mathcal{D}_j}}{\sum_{\mathcal{D}_k\in\mathbb{D}_{\mathcal{V}_I}} \gamma^*_{\mathcal{D}_k}} \times \mathfrak{M}^I_{\mathcal{B}_i} \quad \text{s.t., } \Upsilon^*_{\mathcal{D}_j} = \frac{\gamma^T_{\mathcal{D}_j} + \gamma^Q_{\mathcal{D}_j}}{2} \quad (11)$$

The resource allocation processes in the $\mathbb{G}^{\mathcal{V}_{II}}_{\mathcal{D}}$ and $\mathbb{G}^{\mathcal{V}_{II}}_{\mathcal{D}}$ games are operated as the same manner as the $\mathbb{G}^{\mathcal{V}_I}_{\mathcal{D}}$ game according to (10)-(11). In the lower level stage, the $\mathbb{G}^{\mathcal{V}_I}_{\mathcal{D}}$, $\mathbb{G}^{\mathcal{V}_{II}}_{\mathcal{D}}$ and $\mathbb{G}^{\mathcal{V}_{II}}_{\mathcal{D}}$ games are independently executed in a distributed parallel fashion.

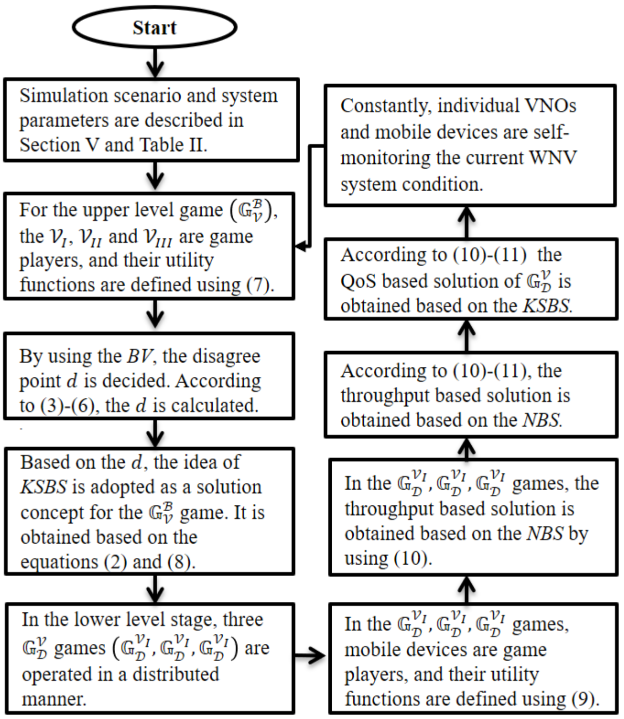
D. MAIN STEPS OF OUR HIERARCHICAL JOINT COOPERATIVE GAME ALGORITHM

Recently, the WNV technology has been proposed as a promising candidate to solve the contradiction between the limited resource and the increasing demands of multiple services. It allows the coexistence of multiple network slices by isolating and sharing network resources. Especially, spectrum is an expensive commodity, so it must be managed among these slices in the most efficient way. However, there are still some challenges to effectively control the slices in the virtualized network platform. This study is the first literature to share the spectrum among multiple VNOs based on the hierarchical cooperative game model, which consists of upper and lower level stages. In the upper level game $\left(\mathbb{G}^{\mathcal{B}}_{\mathcal{V}}\right)$, three VNOsare game players, and they share the $\mathfrak{M}_{\mathcal{B}}$ based on the combination of *KSBS* and *BV*.In the lower level game $\left(\mathbb{G}^{\mathcal{V}}_{\mathcal{D}}\right)$, mobile devices are game players, and they share their corresponding slice $\mathfrak{M}^X_{\mathcal{B}}$ according to the multi-criteria bargaining approach, which combines the ideas of *NBS* and *KSBS*. In the proposed scheme, the upper and lower level games are jointly combined to get reciprocal advantages. Our hierarchical game approach can explore the sequential interactions among VNOsand mobiles, and ensures the excellent flexibility and responsiveness to a dynamically changing WNV environment. Therefore, we can strike an appropriate network performance while guiding selfish agents toward a socially optimal outcome. The primary steps of the proposed scheme are described as follows, and they are described by the following flowchart:

Step 1: To carry out the simulation analysis, system parameters and control factors used in our simulation are displayed in Table 2. Our simulation scenario is described in Section V.

Step 2: At a sequence of time steps, the $\mathbb{G}^{\mathcal{B}}_{\mathcal{V}}$ and $\mathbb{G}^{\mathcal{V}}_{\mathcal{D}}$ games are operated sequentially and interactively to reach a mutually advantages.

Step 3: In the upper level stage, the $\mathbb{G}^{\mathcal{B}}_{\mathcal{V}}$ game is designed to share the $\mathfrak{M}_{\mathcal{B}}$ for the URLLC, eMBB, and mMTC



FLOWCHART 1. Flowchart of the proposed algorithm.

networks. In this game, the $\mathcal{V}_I$, $\mathcal{V}_{II}$ and $\mathcal{V}_{III}$ are game players, and their utility functions are defined using (7).

Step 4: For the $\mathbb{G}^{\mathcal{B}}_{\mathcal{V}}$ game, the idea of *KSBS* is adopted as a solution concept. By using the *BV*, we decide the disagree point d. According to (3)-(6), the d is calculated. And then, the *KSBS* for the $\mathbb{G}^{\mathcal{B}}_{\mathcal{V}}$ game is obtained based on the equations (2) and (8).

Step 5: In the lower level stage, three $\mathbb{G}^{\mathcal{V}}_{\mathcal{D}}$ games are operated in a distributed manner. In these games, individual VNOs distribute their assigned slices into their corresponding devices based on the combination of *NBS* and *KSBS*.

Step 6: In each $\mathbb{G}^{\mathcal{V}}_{\mathcal{D}}$ game, mobile devices are game players, and their utility functions are defined using (9). By considering two different performance criteria, each utility function consists of two sub-functions.

Step 7: In each $\mathbb{G}^{\mathcal{V}}_{\mathcal{D}}$ game, the throughput based solution is obtained based on the *NBS*, and the QoS based solution is obtained based on the *KSBS*. Finally, the resource allocation for each device is decided by using (10) and (11) equations.

Step 8: In our hierarchical joint control paradigm, the $\mathbb{G}^{\mathcal{B}}_{\mathcal{V}}$ and $\mathbb{G}^{\mathcal{V}}_{\mathcal{D}}$ games are sophisticatedly combined, and work together to achieve a reciprocal consensus.

Step 9: Constantly, individual VNOs and mobile devices are self-monitoring the current WNV system condition, and it proceeds to Step 2 for the next game iteration.

V. PERFORMANCE EVALUATION

This section evaluates the performance of our proposed scheme for both inter-slice and intra-slice allocation problems. System-level simulation is conducted by MATLAB software to calculate the average performance. We show the obtained results compared against the existing *RAMSV*, *MSVRA* and *MDSRA* schemes [4], [7], [11]. System parameters and their values are listed in Table 2, and the simulation environment and system scenario are given as follows:

- Simulated the multi-service network platform consists of five BSs, and fifty mobile devices, i.e., $|\mathbb{B}| = 10$ and $|\mathbb{D}| = 300$.
- Each BS has three VNOs for the $\mathcal{S}_I$, $\mathcal{S}_{II}$ and $\mathcal{S}_{III}$ slices.
- Mobile devices randomly select their service types among the URLLC, eMBB, and mMTC networks.
- Devices are randomly distributed over in the BS covering area, and each device $\mathcal{D}_{1\leq i\leq m}$ generates six different type service requests ($\mathcal{R}_{\mathcal{D}}$).
- The arrival process of $\mathcal{R}_{\mathcal{D}}$ is the rate of Poisson process (ρ). The offered range is varied from 0 to 3.0.
- The total spectrum resource of each BS ($\mathfrak{M}_{\mathcal{B}}$) is 150 Gbps, and the equity base amount ($\mathfrak{R}_{\mathcal{B}}$) is 15 Gbps.
- We assume the absence of physical obstacles in the network area.

$$
\begin{aligned}
MCS\left(\mathbb{G}^{\mathcal{V}_I}_{\mathcal{D}}\right) &= \left(\mathcal{D}_j \in \mathbb{D}_{\mathcal{V}_I} | \gamma^T_{\mathcal{D}_j}, \gamma^Q_{\mathcal{D}_j}\right) \\
&= \max_{\left(\gamma^T_{\mathcal{D}_j}, \gamma^Q_{\mathcal{D}_j}\right)} \mathcal{S}^T, \mathcal{S}^Q \\
\text{s.t.,} & \begin{cases}
\mathcal{S}^T = \prod_{\mathcal{D}_j \in \mathbb{D}_{\mathcal{V}_I}} \left(\mathfrak{U}^T_{\mathcal{D}_j}\left(\mathfrak{M}^I_{\mathcal{B}_i}, \mathcal{R}_{\mathcal{D}_j}, \gamma^T_{\mathcal{D}_j}\right) - d_{\mathcal{D}_j}\right) \\
\mathcal{S}^Q = \left\{ \dfrac{\mathfrak{U}^Q_{\mathcal{D}_j}\left(\mathfrak{M}^I_{\mathcal{B}_i}, \mathcal{R}_{\mathcal{D}_j}, \gamma^Q_{\mathcal{D}_j}\right) - d_{\mathcal{D}_j}}{\mathfrak{U}^*_{\mathcal{D}_j}\left(\mathfrak{M}^I_{\mathcal{B}_i}, \mathcal{R}_{\mathcal{D}_j}, \gamma^Q_{\mathcal{D}_j}\right) - d_{\mathcal{D}_j}} = \ldots = \dfrac{\mathfrak{U}^Q_{\mathcal{D}_k}\left(\mathfrak{M}^I_{\mathcal{B}_i}, \mathcal{R}_{\mathcal{D}_j}, \gamma^Q_{\mathcal{D}_j}\right) - d_{\mathcal{D}_k}}{\mathfrak{U}^*_{\mathcal{D}_k}\left(\mathfrak{M}^I_{\mathcal{B}_i}, \mathcal{R}_{\mathcal{D}_j}, \gamma^Q_{\mathcal{D}_j}\right) - d_{\mathcal{D}_k}} \right\} \\
\mathcal{D}_j, \mathcal{D}_k \in \mathbb{D}_{\mathcal{V}_I} \text{and} \mathfrak{U}^T_{\mathcal{D}_j}(\cdot), \mathfrak{U}^Q_{\mathcal{D}_j}(\cdot) > d_{\mathcal{D}_k}
\end{cases}
\end{aligned}
\tag{10}
$$

TABLE 2. System parameters used in the simulation experiments.

Parame-ter	Value	Description
n	10	total number of BSs
m	300	total number of mobile devices
$\mathfrak{M}_{\mathcal{B}}$	150 Gbps	wireless spectrum resource of each MBS
$\mathfrak{R}_{\mathcal{B}}$	15 Gbps	the equity base amount to decide the disagree point
BAU	16 Mbps	the basic allocation unit for resource allocation process
δ	1	control parameters for the $U_{\mathcal{V}_I}(\cdot)$
μ , η	-1.5 , 1	a control parameter for the $U_{\mathcal{V}_{II}}(\cdot)$
ϱ , ε	2.5 , 1	a control parameters for the $U_{\mathcal{V}_{III}}(\cdot)$
β , θ	4 , 0.5	control parameters for the $\mathfrak{U}^T_{\mathcal{D}}(\cdot)$
ξ , κ	1 , -3	a control parameter for the $\mathfrak{U}^Q_{\mathcal{D}}(\cdot)$
Task type	**Requested spectrum ($\mathcal{R}_{\mathcal{D}}$)**	**Service duration /t**
I	256 Mbps	45 time-periods
II	640 Mbps	50 time-periods
III	192 Mbps	25 time-periods
IV	320 Mbps	15 time-periods
V	128 Mbps	40 time-periods
VI	384 Mbps	30 time-periods

- The resource allocation process through the cooperative games is specified in terms of basic allocation units (BAUs) where one BAU is 16 Mbpsin this study.
- The disagreement points ($d_{\mathcal{D}}$) for the lower level stage games arezeros.
- The virtualized multi-service network performance measures obtained on the basis of 100 simulation runs are plotted as functions of the Poisson process (ρ).

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

In Fig. 2, the system throughput in the multi-service platform is shown to evaluate the proposed scheme and the existing *RAMSV*, *MSVRA* and *MDSRA* protocols. In the viewpoint of system operator, the system throughput is a main performance criterion. Essentially, it is synonymous to system resource utilization. It is obvious that our scheme can ensure a much more system throughput than other existing protocols. The main reason of performance improvement is that we make control decisions based on the interactive cooperative game model; our hierarchical approach adaptively approximates the optimal system throughput under widely different and diversified multi-service network situations.

Fig. 3 displays the performance comparison results of device payoff. When the service request ratio increases, the device payoff of all protocols also increases. It is intuitively correct. Compared with the other existing schemes, we can attain the highest device payoff among the four different schemes. In the proposed scheme, each individual VNO adaptively distributes the assigned slice into mobile devices based on the multi-criteria bargaining mechanism. This means that we can guide selfish mobile devices to effectively share the limited resources while considering two different

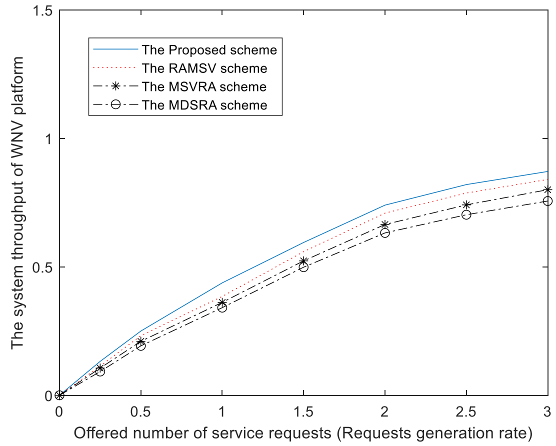


FIGURE 2. System throughput in the WNV system.

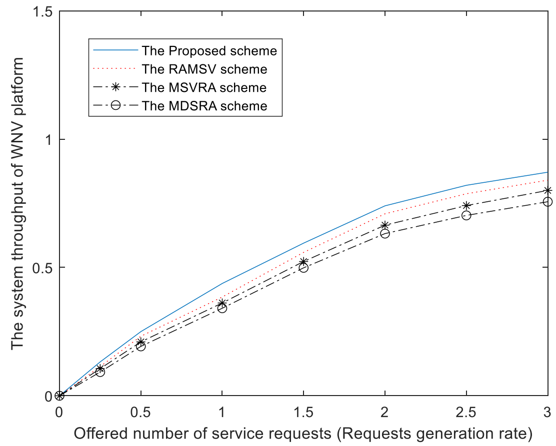


FIGURE 3. Normalized device payoff.

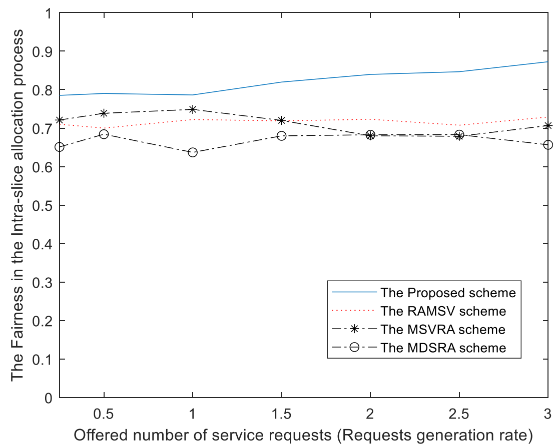


FIGURE 4. Fairness for the intra-slice allocation process.

criteria. Based on the desirable features of NBS and KSBS, our cooperative game based approach is quite adaptable to maximize the device payoff.

Fig. 4 illustrates the Jain's fairness index for mobile devices. As shown in the curves, our proposed scheme outperforms the existing *RAMSV*, *MSVRA* and *MDSRA* protocols by a large margin. In the proposed scheme, each VNO can dynamically allocate its resource based on the combination of *NBS* and *KSBS*. Originally, bargaining solutions are developed to fair-efficiently share the limited resource. Our combined bargaining approach can collectively capture how to negotiate the difference between the throughput and QoS based measures. Therefore, all devices fairly share the limited resource in the intra-slice allocation process. Simulation results confirm that the excellency of our proposed scheme for the fairness index of mobile devices.

VI. SUMMARY AND CONCLUSIONS

With the explosive growth of demands for a variety of wireless communication services, the spectrum scarcity has become an inevitable fact for the network operators. Recently, the WNV technology has been proposed as a promising candidate to effectively maximize the multi-service network performance. In this paper, we investigate a hierarchical resource allocation scheme for the multi-service network system. Based on the WNV technology, we develop a novel hybrid control mechanism. At the upper level stage, the inter-slice allocation process is addressed according to the idea of *KSBS*. In this process, we use the *BV* method to decide the disagreement point of VNOs. At the lower level stage, the intra-slice allocation process is formulated as the multi-criteria resource allocation problem.By combining the *NBS* and *KSBS*, we can effectively negotiate the measure difference. Through the VNO-device coordinated association, our joint control method canreach a mutually acceptable solution under dynamically changing virtual network conditions. Finally, simulation results show the overall performance of multi-service resource allocation problem, which can be well modelled by using WNV technology. Through the numerical analysis, we demonstrate the performance gains brought by our proposed scheme, and verify the superiority of our hierarchical control paradigm by comparing the existing *RAMSV*, *MSVRA* and *MDSRA* schemes.

As a future work, we will consider the allocation problem of different kinds of resources between multiples InPs and MVNOs. Furthermore, it is interesting to formulate the multi-input multi-output orthogonal frequency division method for increasing the flexibility and efficiency of virtualized wireless communications. Moreover, in future versions of our proposed scheme, a new optimization model can be considered related to economic policies of the virtualizing entities, security, and the hardware designs.

AVAILABILITY OF DATA AND MATERIAL

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

COMPETING INTERESTS

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

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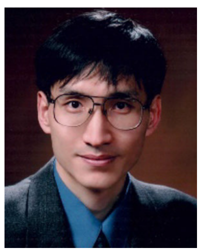

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