ABSTRACT Visible light communication (VLC) is becoming a promising technology of wireless communications, and the co-deployment of radio frequency (RF) and VLC technologies has been investigated in indoor environments to achieve high data rate communications. To explore the benefits of employing both technologies, it is of considerable significance to design intelligent RF/VLC resource management algorithms. In this study, we investigate a new heterogeneous network spectrum allocation scheme based on the cooperative bargaining theory. According to the fundamental concepts of asymmetric Nash, Kalai-Smorodinsky and egalitarian bargaining solutions, we can leverage a mutual consensus to provide a fair-efficient solution. Furthermore, four different allocation rules are adopted to estimate the asymmetry of network agents. Using our step-by-step interactive bargaining method, disproportionate agents are coordinated to effectively share the RF and VLC spectrum resources. It is an essential approach to find the relevant trade-off between conflicting requirements while dynamically responding the hybrid RF/VLC system environment. Numerical simulation results are conducted to corroborate the superiority in performance of the proposed scheme as compared to that obtained with existing state-of-the-art RF/VLC spectrum allocation algorithms.

INDEX TERMS Visible light communications, radio frequency, industrial Internet of Things, cooperative bargaining solutions, allocation rules.

I. INTRODUCTION
Past century has witnessed industrial revolution and Internet revolution, and next century will be dominated by the fourth-industrial revolution, better known as Industry 4.0, which focuses heavily on interconnectivity, automation, machine learning, and real-time data communications. The concept of Industry 4.0 aims at integrating the physical parts of the manufacturing process and cyber parts via networks. Such phenomenon can be effortlessly distinguished from the past ones. Usually, traditional communication networks are the backbone of any successful digital transformation, and the basis for consistent, end-to-end integration. They have been providing a powerful means of data exchange, data controllability, and flexibility to connect various devices. Traditional networks enable to communicate vast amounts of data using a limited number of channels while implementing various communication protocols between digital controllers, field devices, various automation related software tools and also to external systems. However, Industry 4.0 is a blend of computers, cyber-physical systems, and automation working harmoniously to make the production line smarter and more independent. It can take traditional manufacturing and make it better and more efficient in specific ways such as production line monitoring, smart supply chain, predictive analytics and asset monitoring. With the rapid popularization of Industry 4.0, we should provide innovative solutions for industry fields in saving operation cost and improving system reliability. However, limited by the cost of transmission media and communication delay, traditional network infrastructure and platform are not suitable for the development of Industry 4.0. To date, the mainstreaming technique is a self-organizing and mutually interactive mechanism based on a large amount of communication data [1], [2].
The industrial internet of things (IIoT) is one key technology to realize Industry 4.0. It is a new paradigm in information and communication technologies that enables the interconnection of existing industrial devices with additional intelligence. These devices sense, process, and communicate data with each other. For the efficient data processing in IIoT, wireless communications are widely used in Industry 4.0 because of its flexibility and portability. However, even though the IIoT is an emerging prominent paradigm, this promising technology faces numerous technical challenges to serve IIoT services. A large number of IIoT devices access to the Internet frequently, which can produce a huge amount of data in a short period of time. Also, it is challenging for IIoT operators to satisfy individual service preferences. Owning to the scarcity of wireless communication resources, it is noticed that how to efficiently manage the limited spectrum resource has become an important research topic. Another crucial issue is how to guarantee the reliability of IIoT services when lacking the adequate telecommunication infrastructure [2], [3].

With the growing number of IIoT devices, the requirement for data rate has seen an exponential growth in the recent years. Such large quantity of communications requires higher transmission rates, more ubiquitous coverage, and more efficient transmission strategies. However, the use of conventional only radio frequency (RF) systems may fail to fulfill it satisfactorily in the near future; it leads to higher spectrum cost and acute interference issues. For the Industry 4.0, telecommunication communities are searching for alternative techniques to exploit higher frequencies. Visible light communication (VLC) has recently attracted considerable attentions to overcome the scarcity of RF spectrum resource while meeting the high demands of wireless communications services. It uses the deployed light emitting diode (LED) based light sources to transmit data through dimming of light, which is invisible to the eyes. VLC technology possesses a number of interesting features such as, i) significantly higher transmission capacity, ii) relatively secure transmissions, iii) exhaustive reuse of frequency, iv) reduced cost of wireless communications, and v) lower latency compared to traditional RF communication systems [4], [5].

Even though VLC systems offer several advantages, attention must be paid to certain limitations and challenges in stand-alone VLC networks. First, VLC systems perform poorly in non-line-of-sight scenarios owing to the predominantly line-of-sight (LOS) propagation of light. Second, each access point (AP) in VLC networks illuminates only a small confined area compared to a RF AP. Third, achievable data rates vary with spatial fluctuations. To overcome these drawbacks, several researches have recently been focused on the VLC technology with conventional RF communications; it is practically feasible as RF and VLC systems can coexist. This hybrid RF/VLC system has drawn significant interests due to the complimentary nature of RF networks and VLC networks. Usually, standalone VLC networks may not support all IIoT devices in a coverage hole. However, RF networks provide the ubiquitous coverage with moderate data rates. In the indoor scenarios, this RF/VLC combined method can benefit from the wide coverage area that RF systems support and the stable data rates in a small area that VLC systems provide. In addition, VLC signals and RF signals do not interfere with each other. Mutual electromagnetic immunity of the RF and VLC communications can be considered as another advantage. Motivated by these facts, the hybrid RF/VLC system can offer high data rates ubiquitously while guaranteeing a quality-of-service (QoS) requirement [6]–[8].

Apparently, hybrid RF/VLC systems belong to the class of heterogeneous networks (HetNets). As a method to incorporate different access technologies, wireless HetNets contain the potential capabilities of improving the efficiency of spectral resource utilization. Generally, traffic offloading in HetNets has already become an established technique for adding capacity to dense environments where some areas are overloaded. In case of the RF congestion in the hybrid RF/VLC system, this approach has been addressed in the literature that RF networks can offload some part of its traffic to VLC networks. Therefore, the key to utilize the potential performance advantage effectively lies in the reasonable allocation of spectrum resources. However, from a viewpoint of interactive network cooperation, few research work has studied the problem of spectrum resource allocation. In this paper, we investigate the hybrid RF/VLC network infrastructure, and construct the most appropriate spectrum allocation scheme in a cooperative manner [4], [9].

To reason spectrum allocation problems, game theory is well-suited and an effective tool. Originally, game theory is a field of applied mathematics that provides an effective tool in modeling the interactions among independent decision makers. It can describe the possibility to react to the actions of the other decision makers and analyze the situations of conflict and cooperation. Therefore, game theory has become an interesting research topic in a wider range of real life situations, such as economics, political science, sociology, psychology, biology, and so on. Since the early 1990s, computer science and telecommunications have been added to this list. Recently, game theoretic approach is an important paradigm to efficiently allocate the limited network resource. This approach can maximize the system performance under diversified communication environments [11].

A. TECHNICAL CONCEPTS

A cooperative game approach can effectively motivate the participants of a system to work together to maximize social welfare through cooperation. A fundamental assumption of cooperative game is that all the relevant information for determining the rational play of a game is contained in its structural description. Value solution and bargaining theory are two common ways in which participants can be motivated to cooperate. However, two limitations in the value solution, such as lower solution quality and longer computation time, lead to the bargaining theory approach being more suitable for different operating transactions in a multi-agent system. Through cooperative bargaining interactions, the social
welfare of the whole system can be further improved. The bargaining theory was originated by the fundamental papers of J. Nash in 1950’s. He introduced an idealized representation of the bargaining problem and developed a way how to share the obtained gain [10], [11].

Since the 1950’s, several new solutions have been introduced to supplement the original Nash solution. Kalai-Smorodinsky and egalitarian solutions are alternative bargaining solutions to cooperative problems. Usually, most bargaining solutions yield accurate predictions only if they are robust to its specification. This feature will lead to the axiomatization of Nash solution, as well as of the Kalai-Smorodinsky and egalitarian solutions. Therefore, well-known and novel axiomatizations are differently provided for these three best-known bargaining solutions [12]. In this study, we provide a unified framework for comparing these bargaining solutions. This approach aims to bridge the gap between the axiomatic and strategic approaches, and to find a fruitful way of bringing these different bargaining solutions together.

**B. MAIN CONTRIBUTIONS**

In this study, we exploit the hybrid RF/VLC platform with a dynamic spectrum allocation technology. Based on the co-existence environment of VLC and RF networks, heterogeneous IIoT devices can access simultaneously the corresponding RF and VLC APs to maximize their satisfactions. To design a new spectrum allocation scheme, our major objective is to effectively share the limited spectrum resources while optimizing social welfare. For satisfying this goal, multiple IIoT devices work together and act cooperatively under dynamically changing system conditions. In the proposed scheme, we adopt the fundamental ideas of asymmetric Nash, Kalai-Smorodinsky, and egalitarian bargaining solutions and implement our unified bargaining process, which is traced back to sequential negotiations between the device-AP pair. Each bargaining game player shares a common goal and makes a binding commitment based on the exchange of current traffic information. Therefore, the game strategies are coupled with each other to determine the system performance. As far as we can gather, this is the first work that different bargaining concepts are selectively applied to the design of spectrum allocation algorithm in the hybrid RF/VLC system. The key contributions of this study are summarized as follows:

- We investigate the hybrid RF/VLC platform to provide high data rate communication services. Under HetNets environments, IIoT devices participate in a step-by-step interactive bargaining process to effectively share the RF and VLC spectrum resources.
- We study the basic ideas of asymmetric Nash, Kalai-Smorodinsky and egalitarian bargaining solutions and investigate four most prominent allocation rules to estimate the asymmetry of game entities.
- To handle the communication services of IIoT devices, the heterogeneous RF and VLC spectrum resources are effectively shared in a coordinated manner. To get a desirable solution, control decisions are reciprocally combined with each other to ensure the relevant trade-off between conflicting requirements.
- Through the numerical simulation analysis, it is found that our proposed scheme can lead to an improvement of more than 10% and 20% in the achievable system throughput, device’s payoff and fairness as compared to that obtained with the existing state-of-the art protocols.

**C. ORGANIZATION**

The remainder of this paper is organized as follows. The related work is briefly reviewed in Section II. In Section III, we introduce the hybrid RF/VLC infrastructure. Then, the principles and characteristics of asymmetric Nash, Kalai-Smorodinsky and egalitarian solutions are presented to formulate our unified bargaining model, which has a significant impact on the RF/VLC system performance. In addition, to help readers understand better, the main steps of our proposed algorithm are explained in detail. Section IV provides extensive simulation results to evaluate the performance of the proposed scheme while verifying the effectiveness of our approach. Finally, we conclude this study and discuss future worthwhile research directions in Section V.

**II. RELATED WORK**

Owing to the difference of RF and VLC communications, efficient resource allocation problem becomes crucial in the hybrid RF/VLC system. Several resource allocation schemes exist for offering a higher achievable performance. The paper [19] addresses the joint allocation problem of assigning users to Aps, and schedules them to resource blocks. An improved proportional fairness algorithm is proposed to take into account the fairness of the hybrid heterogeneous RF/VLC platform. In this algorithm, the system resources are efficiently utilized by allowing subscribers to dynamically select APs based on the priority while maximizing the data rate and user fairness index [19]. In [20], authors address the radio resource allocation problem for full-duplex system. Due to the self-interference and inter-user interference, the problem is coupled between uplink and downlink channels. Based on game theory, a new iterative algorithm is proposed by modelling the problem as a non-cooperative game between the uplink and downlink channels. The algorithm iteratively carries out optimal uplink and downlink resource allocation until a Nash equilibrium is achieved [20].

L. Song et al. demonstrate the applications of gametheoretic models to study the radio resource allocation issues in Device-to-device (D2D) communications [21]. The game theoretic models are useful for designing radio resource allocation algorithms to achieve stable and efficient solutions by allowing D2D users to efficiently reuse the licensed spectrum of cellular users. These models have been categorized based on the types of games. For D2D direct communication, non-cooperative game and auction game models are suitable to
solve the resource allocation problems. For D2D LANs, collaboration among mobiles is required, and thus cooperative game models such as the coalition formation games can be used. They have also outlined potential research directions on developing game theoretic models to solve several important radio resource management problems for D2D communication [21].

In [9], the Heterogeneous Network Bandwidth Aggregation (HNBA) scheme investigates the co-existence situation of RF cells, which are omnidirectional small cells, and VLC cells, which are directional small cells. In this infrastructure, interference can be mitigated in the provisioning process and multiple cells can perform data transmission simultaneously without contention. The HNBA scheme can quantify the system performance of spectrum aggregation with respect to minimum average system delay. In particular, an adaptive delay control algorithm in the heterogeneous system is developed; it differs from other existing literatures. For the heterogeneous network platform, the average system delay is derived for the spectrum aggregated scenario, and it is theoretically proved that the average system delay with a spectrum aggregation technique can be minimized. Extensive simulation results imply that when contentention and backoff mechanisms are considered [9].

The paper [7] proposes the Cooperative Traffic Load Balancing (CTLB) scheme for VLC and RF networks. The main goal in this paper is to investigate a cooperative load balancing issue for a hybrid VLC-RF system, where a salient problem is the appropriate formation of VCL cells. To solve the essential load balancing problem in the context of VLC-RF hybrid system, both centralized and distributed resource-allocation algorithms are designed for implementing a proportional fairness scheduler. By employing the mean spectrum efficiency of different VLC cell formations, the system throughput and fairness are analyzed for the heterogeneous network platform. In addition, various VLC cell formations, ranging from a regular cell-layout associated with different frequency reuse patterns to merged cells by employing an advanced transmission method, are investigated. The simulation results demonstrate that the CTLB scheme achieves the highest throughput and fairness in most of the scenarios considered [7].

L. Yang et al. propose the Heterogeneous Network Resource Allocation (HNRA) scheme for the VLC-RF platform [13]. VLC and RF networks are controlled by different subsystems, respectively. They investigate a distributed joint resource allocation problem and design two kinds of resource allocation strategies to control the limited spectrum resources with maximum fairness. With a single RF AP and several VLC APs, they implement the weight-based maximum and minimum allocation methods and design the spectrum allocation algorithm with weights to reduce the dynamic range. Through the fairness index, the key technologies of VLC-RF combined platform are analyzed and compared with the traditional HetNet resource management protocols. The HNRA scheme can maximize the fairness among IoT devices while improving the utilization of the resource. Finally, they verify the effectiveness of the HNRA scheme, which has a better adaptability to the hybrid RF/VLC system [13].

Until now, some existing protocols have proposed novel ideas for the spectrum allocation algorithms based on the hybrid RF/VLC platform. However, none of research literatures consider the combined bargaining approach from an interactive perspective. Due to the desirable characteristics of cooperative game theory, our proposed scheme can get a well-balanced system performance for the hybrid RF/VLC platform.

III. THE PROPOSED RF/VLC SPECTRUM ALLOCATION ALGORITHM

This section presents the hybrid RF/VLC system infrastructure and introduces an operation scenario. Then, based on the different bargaining solutions, the proposed bargaining game model is formulated to share the RF and VLC spectrum resources. Finally, the main steps of our proposed algorithm are described.

A. HYBRID RF/VLC PLATFORM AND UNIFIED BARGAINING GAME

In this paper, a joint network model is considered to establish the hybrid RF/VLC platform. We consider heterogeneous APs, i.e., RF or VLC APs, that provide wireless connections to multiple IIoT devices; they are positioned at different locations in an indoor environment. RF and VLC APs interact regularly for the joint resource management, and contact to the Internet through backhaul links. Although both VLC and RF transmissions use electromagnetic radiation for the information transfer, their properties differ significantly. Therefore, they can overlap with different data access rates. We assume that the hybrid RF/VLC network infrastructure composed of a single RF AP \( R \) and multiple VLC APs, i.e., \( \mathcal{V} = \{ V_1, \ldots, V_n \} \). A number of IIoT devices, i.e., \( \mathcal{D} = \{ D_1, \ldots, D_m \} \), are located in the coverage region of both APs, which provide data transmission services for IIoT devices. This framework can easily be extended to a multiple RF APs scenario. Fig.1 illustrates the hybrid RF/VLC platform architecture [6], [13].

Each individual device is considered to be equipped with an RF front-end and a photo-diode. Therefore, the
collaboration between RF and VLC is realized by the dual spectrum capability, which enables IIoT devices to aggregate different spectrum resources from both VLC and RF networks. Therefore, at a given time, IIoT devices can connect simultaneously both networks through two parallel communication links. The $\mathcal{R}$ and each $\mathcal{V}_{i, j} \leq n$ have their spectrum resources, i.e., $\mathcal{M}_R$ and $\mathcal{M}_V$, respectively. They have multiple signal reception interfaces that allow simultaneous connections to corresponding IIoT devices. Each IIoT device ($\mathcal{D}_{1, j} \leq n$) generate communication tasks according to a Poisson process and accesses its corresponding APs via wireless communications. The operational timeline is discretized into time slots to make spectrum allocation; it is the same scale of communication task arrivals, which is a common assumption in the hybrid RF/VLC system [14].

For the $\mathcal{D}_j$, the totally generated communication workload is $\Upsilon_{D_j} = \Upsilon_{RF}^{D_j} + \Upsilon_{VLC}^{D_j}$ where $\Upsilon_{RF}$ and $\Upsilon_{VLC}$ are the $\mathcal{D}_j$’s RF and VLC communication amounts, respectively. However, the RF and VLC spectrum resources are limited. Therefore, effective spectrum allocation strategies should be considered to improve the resource efficiency. To address the RF/VLC spectrum sharing problem, we formulate three bargaining games. At a time period, each individual $\mathcal{D}_j$ processes its bargaining games with its corresponding $\mathcal{V}_i$ and $\mathcal{R}$. In the $\mathcal{D}_j$, the bargaining game ($\mathcal{G}_{D_j}$) is designed to decide the amounts of $\Upsilon_{RF}^{D_j}$ and $\Upsilon_{VLC}^{D_j}$. In the $\mathcal{V}_i$ and $\mathcal{R}$, two bargaining games, i.e., $\mathcal{G}_{V_i}$ and $\mathcal{G}_{R}$, are formulated to share the $\mathcal{M}_V$ and $\mathcal{M}_R$, respectively. It is noteworthy that our proposed unified bargaining game formulates the $\mathcal{R} - \mathcal{V} - \mathcal{D}$ association, and the $\mathcal{G}_{D_j}$, $\mathcal{G}_{V_i}$ and $\mathcal{G}_{R}$ games are designed based on the concepts of different bargaining solutions. These games are operated in a cooperative manner, and they are repeated in a step-by-step interactive fashion. Formally, we define the $\mathcal{G}_{D_j}$, $\mathcal{G}_{V_i}$ and $\mathcal{G}_{R}$ game entities, i.e.,

$$\mathcal{G} = \{ \mathcal{G}_{D_j}^{1 \leq n}, \mathcal{G}_{V_i}^{1 \leq n}, \mathcal{G}_{R} \}$$

- $\mathcal{D}$ is the set of IIoT devices and $\mathcal{V}$ is the set of VLC APs in the heterogeneous RF/VLC platform.
- In the $\mathcal{G}_{D_j}$, RF and VLC communication services are game players. $\Upsilon_{RF}^{D_j}$ and $\Upsilon_{VLC}^{D_j}$ are their strategies, and $U_{RF}^{D_j}$ and $U_{VLC}^{D_j}$ are their utility functions.
- In the $\mathcal{G}_{V_i}$, $\mathcal{M}_V$ is the $\mathcal{V}_i$’s total VLC spectrum capacity, and $\mathcal{D}_{V_i}$ is the set of IIoT devices covered by the $\mathcal{V}_i$. $\mathcal{D}_j \in \mathcal{D}_{V_i}$ is a game player, and $\mathcal{M}_V^{D_j}$ is the allocated VLC spectrum amount for the $\mathcal{D}_j$; it is the $\mathcal{D}_j$’s strategy. The $U_{D_j}^{V_i}$ is the $\mathcal{D}_j$’s utility function.
- In the $\mathcal{G}_{R}$, $\mathcal{M}_R$ is the $\mathcal{R}$’s total RF spectrum capacity, and the $\mathcal{D}_j \in \mathcal{D}$ is a game player, and $\mathcal{M}_R^{D_j}$ is the allocated RF spectrum amount for the $\mathcal{D}_j$; it is the $\mathcal{D}_j$’s strategy. The $U_{D_j}^{R}$ is the $\mathcal{D}_j$’s utility function.

Discrete time model $t \in \{t_1, \ldots, t_n, t_{n+1}, \ldots\}$ is represented by a sequence of time steps. The length of $t_c$ matches the event time-scale of $\mathcal{G}_{D_j}$, $\mathcal{G}_{V_i}$, and $\mathcal{G}_{R}$.

### B. The Fundamental Ideas of Three Bargaining Solutions

To characterize the fundamental ideas of bargaining solutions, we assume a $n$-player bargaining problem. $\mathbb{R}^n$ denotes the $n$-dimensional Euclidean space, and let $(S, N, f)$ be a bargaining problem: $S \subset \mathbb{R}^n$ is a nonempty and finite set, $N = \{1, \ldots, i, \ldots, n\}$ be the set of players, and $f$ is a function from $\mathbb{R}^n$ to $\mathbb{R}$ for any $x, y \in \mathbb{R}^n$, we write $x \geq y (x \succ y$, resp.) if for any $i \in S, x_i \geq y_i (x_i > y_i$, resp.). $U$ is the set of feasible allocations. The relationship between $f$ and $U$ is analogous to that between a transformation function and a production possibility set in producer theory. As the Euclidean metric on $\mathbb{R}^n$, $d \in S$ is the disagreement point. $W \in \mathbb{R}^n_{+}$ is a vector of players’ asymmetry where $\mathbb{R}^n_{+} = \{x \in \mathbb{R}^n \mid x > 0\}$.

Weighted by $\mathcal{W}$, the asymmetric Nash bargaining solution (ANBS) is defined as the following maximization problem [15]:

$$ANBS(S, d, W) = \arg \max_{x \in U} \prod_{i \in N} (x_i - d_i)^{W_i},$$

s.t., \quad $x \in f (S, d) \geq d \quad (1)$

To define the asymmetric Kalai-Smorodinsky bargaining solution (AKSBS), we define the utopia point \(A(S)\) where \(A(S) = \max \{x \mid (x_i \geq x_i) \in S\}\) and the weak Pareto set $WP(S) \equiv \{x \in S \mid x \succ y \forall y \notin S\}$. The main idea of AKSBS is to equalize the fractions of their ideal payoffs that players achieve. Therefore, the AKSBS is defined as follows [16]:

$$AKSBS(S, d, \mathcal{W}) = \left\{i, j \in N \mid \left(\frac{x_i - d_i}{x_i - d_i}\right) = \frac{W_i \times \mathcal{A}_i(S)}{W_j \times \mathcal{A}_j(S)} \right\} \cap WP(S) \quad (2)$$

As a proportional bargaining solution based on the weight, the asymmetric egalitarian bargaining solution (AENS) is defined as follows [17]:

$$AENS(S, d, \mathcal{W}) = \left\{i, j \in N \mid (\mathcal{V}_i \times (x_i - d_i)) = (\mathcal{W}_j \times (x_j - d_j)) \right\} \quad (3)$$

To define the $\mathcal{W}$, we consider the bankruptcy problem under the assumption that claimants have reference-dependent preferences. In a bankruptcy problem, an arbitrator must allocate a finite and perfectly divisible resource among several claimants whose claims sum to a greater amount than what is available. To estimate different specifications for
claimants’ reference, four most prominent rules, such as Proportional (P), Constrained Equal Awards (CEA), Constrained Equal Losses (CEL), and Small Claims First (SCF), are proposed on the basis of the level of utilitarian and maxmin welfare that they generate. In this study, we assume that claimants in the bankruptcy problem are players in our bargaining games, and players’ references are given as their asymmetric bargain weights [18].

Let \( E \in \mathbb{R}_+ \) denote the endowment of the resource to be allocated and each claimant \( i \in N \) has a claim \( c_i \in \mathbb{R}_+ \) on \( E \). The vector \( c = (c_1, \ldots, c_n) \) collects individual claims where \( E = \sum_{i\in N} c_i \). A bankruptcy problem is a pair \((c, E) \in \mathbb{R}_+^n \times \mathbb{R}_+\), where \( c \) is such that \( E \geq c \). Each rule is a function that associates to any problem \((c, E)\), and provides a unique awards vector. The \( P \) rule \((P(c, E))\) allocates the endowment proportional to claims. For the \( c_i \), the \( P \) award is given as follows [18]:

\[
P_{i\in N}(c, E) = \Gamma \times c_i, \quad \text{s.t.,} \quad \Gamma = E/\varepsilon \tag{4}
\]

The CEA rule \((CEA(c, E))\) assigns equal awards to all claimants subject to the requirement that no one receives more than his claim. For the \( c_i \), the CEA award is given by [18]:

\[
CEA_{i\in N}(c, E) = \min\{c_i, \Gamma\}, \quad \text{s.t.,} \quad \sum_{i\in N} \min\{c_i, \Gamma\} = E \tag{5}
\]

The CEL rule \((CEL(c, E))\) assigns an equal amount of losses to all claimants subject to the requirement that no one receives a negative amount. For the \( c_i \), the CEL award is given by [18]:

\[
CEL_{i\in N}(c, E) = \max\{0, c_i - \Gamma\}, \quad \text{s.t.,} \quad \sum_{i\in N} \max\{0, c_i - \Gamma\} = E \tag{6}
\]

The SCF rule \((SCF(c, E))\) assigns to each agent the minimum amount between his claim and what remains of the endowment, starting from the first. To define the \( SCF_i(c, E) \), let \( x_1 < \cdots < x_n \) denote an order on the set of claimants according to their claims and starting from the lowest; ties are broken randomly. The \( SCF_i(c, E) \) is given by [18]:

\[
SCF_{i\in N}(c, E) = \min\left\{c_i, \max\left\{\left(E - \sum_{j \neq i} c_j\right), 0\right\}\right\} \tag{7}
\]

C. THE INTERACTIVE BARGAINING GAME IN THE HYBRID RF/VLC PLATFORM

To develop our interactive bargaining game, we construct the \( G_{D_1 \leftarrow \text{RF}} \), \( G_{V_1 \leftarrow \text{VLC}} \), and \( G_R \) games. They are interacting with one another during a sequence of time steps. At each time period, the \( G_{D_1} \) is designed for the \( D_1 \)'s RF and VLC communication services. This game decides the \( \Upsilon_{D_1}^{RF} \) and \( \Upsilon_{D_1}^{VLC} \) values to maximize the \( D_1 \)'s payoff. At the time \( t_c \), the \( U_{D_1}^{RF}(\cdot) \) and \( U_{D_1}^{VLC}(\cdot) \) are defined as follows:

\[
\begin{align*}
U_{D_1}^{RF}(\cdot) &= \left( \Upsilon_{D_1}^{RF}(\cdot), U_{D_1}^{RF}(\cdot), \rho_{D_1}^{RF} \right) \\
&= \left( \exp\left( \frac{\Upsilon_{D_1}^{RF}}{\Upsilon_{D_1}^{RF}} \right) - \exp\left( -\frac{\Upsilon_{D_1}^{RF}}{\Upsilon_{D_1}^{RF}} \right) \right) \times \left[ \alpha - \frac{\rho_{D_1}^{RF}}{\varepsilon} \right] \\
U_{D_1}^{VLC}(\cdot) &= \left( \Upsilon_{D_1}^{VLC}(\cdot), U_{D_1}^{VLC}(\cdot), \rho_{D_1}^{VLC} \right) \\
&= \log\left( \frac{\Upsilon_{D_1}^{VLC}}{\Upsilon_{D_1}^{VLC} + \eta} \right) \times \left[ \beta - \frac{\rho_{D_1}^{VLC}}{\varepsilon} \right]
\end{align*}
\]

s.t., \( \Upsilon_{D_2} \geq \Upsilon_{D_1}^{RF} \), \( \Upsilon_{D_3} \geq \Upsilon_{D_1}^{VLC} \) and \( \Upsilon_{D_4} = \Upsilon_{D_2}^{RF} + \Upsilon_{D_3}^{VLC} \)

(8)

where \( \rho_{D_1}^{RF} \) and \( \rho_{D_1}^{VLC} \) are the using RF and VLC spectrum amounts at time \( t_c \), respectively. \( \alpha \) is a control parameter for the \( U_{D_1}^{RF}(\cdot) \), and \( \beta, \eta \) are control parameters for the \( U_{D_1}^{VLC}(\cdot) \).

Since all game players in the \( G_{D_1} \) are the \( D_1 \)'s communication services, the solution concept should be strongly concerned the egalitarianism for game players. In this case, the \( AEB \) is preferred for the solution concept of \( G_{D_1} \). It is given by:

\[
AEB \left( \left( U_{D_1}^{RF}(\cdot), U_{D_1}^{VLC}(\cdot), \Upsilon_{D_1}^{RF}(\cdot), \Upsilon_{D_1}^{VLC}(\cdot), d_{D_1}, W_{D_1} \right) \right) = \left\{ \left( \Upsilon_{D_1}^{RF}(\cdot), \Upsilon_{D_1}^{VLC}(\cdot), d_{D_1}, W_{D_1} \right) \right\}
\]

(9)

where \( d_{D_1}^{RF} \) and \( d_{D_1}^{VLC} \) (or \( W_{D_1}^{RF} \) and \( W_{D_1}^{VLC} \)) are disagreement points (or weight factors) for RF and VLC communication services, respectively. Weight factors are decided by considering the comparative traffic congestion ratio. For example, if the RF network is heavily congested than the VLC network, the weight factor of VLC network increases, relatively.

Contrast to the \( G_{D_1} \), the \( G_{V_1} \) and \( G_R \) games are operated in the \( V_1 \) and \( R \), respectively. First, the \( G_{V_1} \) game is developed to share the \( \mathcal{M}_{V_1} \), and all game players are devices in the \( V_1 \). As a game player, the utility function of \( D_1 \in \mathcal{D}_{V_1} \), i.e., \( U_{D_1}^{V_1}(\cdot) \), is defined as follows:

\[
U_{D_1}^{V_1}(\mathcal{M}_{V_1}, \mathcal{M}_{V_1}^{D_1}, \mathcal{D}_{V_1}) = \exp\left( \frac{\exp\left( \frac{\mathcal{M}_{V_1}^{D_1}}{\mathcal{M}_{V_1}} \right) - \exp\left( -\frac{\mathcal{M}_{V_1}^{D_1}}{\mathcal{M}_{V_1}} \right)}{\exp\left( \frac{\mathcal{M}_{V_1}}{\mathcal{M}_{V_1}} \right) + \exp\left( -\frac{\mathcal{M}_{V_1}}{\mathcal{M}_{V_1}} \right)} \right) - \zeta
\]

s.t., \( \mathcal{M}_{V_1} \geq \sum_{D_1 \in \mathcal{D}_{V_1}} \mathcal{M}_{V_1}^{D_1} \)

(10)
where $\zeta$ is a control parameter for the $U^V_{D_j} (\cdot)$. In the $G_{V_i}$, relatively small game players share the $\mathfrak{M}_{V_i}$ for the higher data rate service. In this case, the difference of players’ requirements for the $\mathfrak{M}_{V_i}$ needs the independence of alternatives other than the disagreement point. Therefore, the ANBS is preferred for the solution concept of $G_{V_i}$. It is given by:

$$
\text{ANBS} \left( \left( U^V_{D_j} (\cdot), d^V_{D_j}, W^V_{D_j} \right) \right) = \arg \max \left\{ \sum_{D_j \in D_{V_i}} \left( U^V_{D_j} (\cdot) - d^V_{D_j} \right) \right\}_{D_j \in D_{V_i}}
$$

(11)

where $d^V_{D_j}$ and $W^V_{D_j}$ are the disagreement point and weight factor of $D_j$, respectively, in the $G_{V_i}$. To get the $W^V_{D_j}$ value, we adopt the $P$, $CEA$, $CEL$ and $SCF$ allocation rules using (4)-(7), and estimate a mathematical average of them. Finally, it is given by considering the minimum weight and relative normalization:

$$
W^V_{D_j} = \min \left( \frac{\mathcal{J}^V_{D_j}}{\mathcal{J}^V_{D_j}}, \Theta \right) \left( \sum_{D_j \in D_{V_i}} \min \left( \frac{\mathcal{J}^V_{D_j}}{\mathcal{J}^V_{D_j}}, \Theta \right) \right)
$$

(12)

where $\mathcal{J}^V_{D_j}$ is the requested $V_i$ spectrum amount from the $D_j$, and $R^V_{D_j}$ is the vector of $\mathcal{J}^V_{D_j}$. Second, the $G_R$ game determines the $W^R_{D_j}$ value to distribute the limited $\mathfrak{M}_{R}$ resource. In this game, the $D_j \in D$ is a game player, and its utility function $(U^R_{D_j} (\cdot))$ is defined as follows:

$$
U^R_{D_j} \left( \mathfrak{M}_R, D, \mathfrak{M}_D^R \right) = \frac{\log \left( \frac{\psi + \mathfrak{M}_D^R}{\phi + \mathfrak{M}'} \right)}{\log \left( \frac{\psi + \mathfrak{M}_D^R}{\phi + \mathfrak{M}'} \right)}, \quad \text{subject to } \mathfrak{M}_R \geq \sum_{D_j \in D} \mathfrak{M}_D^R
$$

(13)

where $\psi$ and $\phi$ are adjustment factors for the $U^R_{D_j} (\cdot)$. In the $G_R$, relatively large game players share the $\mathfrak{M}_R$ for the lower data rate service. In this case, it is clear that one player’s gain in a negotiation relative to the other players must increase or decrease monotonically with respect to that player’s weight factor relative to that of the other players. Therefore, the AKSBS is preferred for the solution concept of $G_R$. It is obtained as follows:

$$
\text{AKSBS} \left( \left( U^R_{D_j} (\cdot), d^R_{D_j}, W^R_{D_j} \right) \right) = \left\{ \begin{array}{ll}
U^R_{D_j} \left( \mathfrak{M}_R, D, \mathfrak{M}_D^R \right) - d^R_{D_j} & \text{if } \mathfrak{M}_R \geq \sum_{D_j \in D} \mathfrak{M}_D^R \\
U^R_{D_j} \left( \mathfrak{M}_R, D, \mathfrak{M}_D^R \right) - d^R_{D_j} & \text{otherwise}
\end{array} \right.
$$

(14)

where $d^R_{D_j}$ and $W^R_{D_j}$ are the disagreement point and weight factor of $D_j$ and $D_j$, respectively. In the $G_R$, $W^R_{D_j}$ is estimated as the same manner as the $G_{V_i}$ game.

### D. MAIN STEPS OF OUR RF/VLC SPECTRUM ALLOCATION ALGORITHM

In this article, we propose a novel spectrum allocation algorithm to characterize the hybrid RF/VLC platform. To find the best fair-efficient solution, we adopt the ideas of $AEB_{S}, ANBS$ and $AKSBS$. For the decision of game player’s asymmetry, the $P$, $CEA$, $CEL$ and $SCF$ rules are used. First, in a parallel fashion, multiple $G_{D_j \in D}$ games are operated in each individual device. This game decides the amounts of RF and VLC communication services. Second, the $G_{V_i}$ game is operated in each individual $V_i \in V$ in a distributed manner. This game allocates the $\mathfrak{M}_{V_i}$ into the corresponding devices, i.e., $D_j \in D_{V_i}$. Third, for all devices, the $G_R$ proceeds the $G_R$ game to share the $\mathfrak{M}_R$. During discrete time periods, the $G_{D_j}$, $G_{V_i}$ and $G_R$ games are operated repeatedly in a step-by-step online manner. Owing to the desirable characteristics of the bargaining solutions and allocation rules, we can effectively satisfy contradictory requirements of game entities under dynamic RF and VLC network environments. The main steps of our proposed algorithm can be described as follows:

- **Step 1:** To share the RF and VLC network spectrum resources, the values of the control factors and parameters are listed in Table 1, and the simulation testbed is given in Section IV.

- **Step 2:** At each time epoch, multiple devices in the $D$ generate their communication tasks in the hybrid RF/VLC system platform.

- **Step 3:** In each individual $D_j \in D$, the $G_{D_j}$ game is operated in a dispersive manner while contacting its corresponding $V_i \in V$ and $R$. According to (8), the utility functions, i.e., $U^R_{D_j} (\cdot)$ and $U^V_{D_j} (\cdot)$, are defined.

- **Step 4:** Based on the concept of $AEB_{S}$, the solution of $G_{D_j}$ game is determined using (9). At this time, the player’s weight factor is estimated as each network’s relative traffic load.

- **Step 5:** In each individual $V_i$, the $G_{V_i}$ game is operated in a decentralized manner. In the $G_{V_i}$ game, the $D_j$’s utility function, i.e., $U^V_{D_j} (\cdot)$, is defined according to (10).

- **Step 6:** Using (11), the solution of $G_{V_i}$ game is given while dynamically adjusting the $W^V_{D_j} (\cdot)$ value according to (12).

- **Step 7:** The $R$ proceeds the $G_R$ game to share the $\mathfrak{M}_R$. In the $G_R$ game, the $D_j$’s utility function, i.e., $U^R_{D_j} (\cdot)$, is defined according to (13).

- **Step 8:** Based on the equation (14), the solution of $G_R$ game is obtained while adjusting the $W^R_{D_j} (\cdot)$ value as the same manner as the $G_{V_i}$ game’s decision process.

- **Step 9:** During discrete time periods, the $G_{D_j}$, $G_{V_i}$ and $G_R$ games work together to get the optimal performance in the hybrid RF/VLC system.
TABLE 1. System parameters used in the simulation experiments.

| Parameter | Value | Description |
|-----------|-------|-------------|
| \(n\) | 5 | the total number of VLC APs |
| \(m\) | 20 | the total number of IIoT devices |
| \(\alpha\) | 2 | a control parameter for the \(U^R_G(\cdot)\) |
| \(\beta, \eta\) | 5, 1 | control parameters for the \(U^G_G(\cdot)\) |
| \(\zeta\) | 1 | a control parameter for the \(U^V_G(\cdot)\) |
| \(\psi, \varphi\) | 1, 2 | adjustment factors for the \(U^V_G(\cdot)\) |
| BSU | 4 Mbps | the minimum amount of spectrum allocation |
| \(d^0\) | [0, 0] | disagreement point of \(G_0\) game |
| \(d^V\) | [\(\ldots\) 0 \(\ldots\)] | disagreement point of \(G_v\) game |
| \(d^R\) | [\(\ldots\) 0 \(\ldots\)] | disagreement point of \(G_R\) game |
| \(\theta\) | 0.9 | the upper bound for the \(W^V\) |
| \(\varpi\) | 400 Gbps | total communication power of each \(E\) |
| \(\varpi_R\) | 80 Gbps | total computing capacity of \(D\) |

### Step 10: Constantly, individual game entities self-monitor the current system environments, and explore to achieve mutual advantages in a coordinated manner. Proceed to Step 2 for the next game process.

### IV. PERFORMANCE EVALUATION

In this section, we conduct simulation experiments and present numerical results to substantiate our interactive bargaining approach. The proposed spectrum allocation scheme is simulated based on MATLAB while comparing with other existing methods such as \(HNBA\), \(CTLB\) and \(HNRA\) protocols in [9], [7], [13]. The simulation scenario and specific experimental testbed need to below basic assumptions:

- The simulated hybrid RF/VLC system platform consists of one \(R\), five VLC APs and twenty IIoT devices where \(|V|=5\) and \(|D|=20\). Devices are located in the indoor area of their corresponding APs.
- Total communication capacity \(\varpi_R\) of \(R\) is 400 Gbps, and total communication capacity \(\varpi_V\) of each individual \(V\) is 80 Gbps.
- The disagreement points \((d^D, d^V, d^R)\) of all bargaining games are assumed as zeros.
- To reduce computation complexity, the amount of spectrum allocation process is specified in terms of basic spectrum units (BSUs), where one BSU is the minimum amount (e.g., 4 Mbps in our system) of spectrum allocation.
- Wireless communication tasks are generated in each individual IIoT device. At each time epoch, the generation process for task services is Poisson with rate \(\Lambda\) (services/t), and the range of offered workload was varied from 0 to 3.0.
- Six different communication task services are assumed based on their communication requirements, and service duration times.
- System performance measures obtained on the basis of 100 simulation runs are plotted as a function of the offered task request workload.

In Fig.1, it is observed that the average system throughput as a function of increasing workload rate, for different RF/VLC system spectrum allocation protocols. In our simulation model, the system throughput is the rate at which communication tasks are successfully processed. From the simulation results, we can observe that the throughput of our proposed scheme is higher than that of the other existing schemes when the workload rate increases. The reason is that our interactive bargaining approach can dynamically allocate the limited spectrum resources by considering the asymmetry of network entities. Therefore, we can adapt the dynamics of RF/VLC system under widely different situations.

The comparison in terms of normalized IIoT device payoffs is performed and the simulation results are shown in Fig.2. These results are consistent with the results of Fig.1. The reason is that if the total communication amount of each device increases, the system throughput also increases. Therefore, these two performance criteria are strongly related and mutually reinforcing. This simulation outcome confirms that individual IIoT devices in the proposed scheme can effectively handle their communication tasks based on the different control viewpoints of \(ANBS\), \(AKSBS\) and \(AEBS\). This feature makes spectrum allocation decisions adaptively from low to heavy workload rates while leading to an optimized system performance.

In Fig.3, we plot the fairness per each IIoT device. We can see from the figure that our proposed scheme can achieve the best fairness than the \(HNBA\), \(CTLB\) and \(HNRA\) protocols for the range of offered workload rates. Traditionally, bargaining
solutions are paradigmatic for the fairness issue, and the major characteristic of ANBS, AKSBS and AEBS is to provide a fair-efficient solution with taking the mutual advantages. In addition, the asymmetry of game entities is effectively estimated according to the $P$, CEA, CEL and SCF rules. It ensures a preferable outcome in the fairness comparison. The simulation results shown in Fig.1 to Fig.3 demonstrate that the proposed scheme can strike an appropriate performance balance under widely diversified communication workload intensities in the hybrid RF/VLC platform.

V. SUMMARY AND CONCLUSION

In this article, the spectrum allocation problem for a hybrid RF/VLC system has been addressed. To tackle this problem in an efficient way, the bargaining concepts borrowed from ANBS, AKSBS and AEBS are observed, and asymmetry factors of network entities are adaptively estimated according to the $P$, CEA, CEL and SCF rules. Therefore, our unified bargaining approach can leverage a mutual consensus to provide a fair-efficient solution. During the step-by-step interactive process, we allocate the limited RF and VLC spectrum resources to ensure the conflicting requirements of multiple IIoT devices. Under widely different and diversified RF/VLC system conditions, the best response dynamics is a major novelty of our proposed scheme. Finally, we perform extensive experimental simulations to prove the effectiveness of our proposed method. Based on numerical simulation results, it is concluded that the proposed scheme can achieve performance gains compared to the existing HNBA, CTLB and HNRA schemes.

Our future work is to test the validity and performance of our proposed algorithm on a realistic experimental testbed. Furthermore, as there are still potentials in each decision making process of our unified bargaining games, we will attempt to revise and improve each of our three bargaining processes in the future. As the direction of this approach, we can devote attention to the corresponding AP selection problem and the handoff control problem for mobile IIoT devices.

COMPETING OF INTERESTS

The author declares that there are no competing interests 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 the statistical analysis.

AVAILABILITY OF DATA AND MATERIAL

The data used to support the findings of this study are available by contacting the corresponding author at swkim01@sogang.ac.kr.

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