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A Novel Local and Global Cooperative Approach for Distributed Mobile Cloud Computing

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ABSTRACT In the cloud service paradigm, service providers aim to cost-efficiently serve Internet of Things (IoT) devices' applications that often request computation-intensive services. In this study, we focus on the cloud resource sharing problem in the distributed mobile cloud computing (DMCC) platform. By considering different IoT applications and distributed cloud infrastructure, we design a novel DMCC resource sharing scheme for data offloading services. Based on the cooperative game theory, five different value solutions are adopted, and they are implemented for each case cooperative process to provide the fair-efficient solution. According to the service characteristics, our proposed scheme explores the mutual benefits of local and global MCC providers' interactions, and effectively shares the distributed cloud resources. To dynamically adapt the current DMCC system conditions, our approach can provide an appropriate guidance to improve the efficiency of cloud resource usage while enhancing the service quality. The main novelty of our proposed scheme is the ability to leverage a reciprocal consensus between different control viewpoints. Therefore, we can ensure a relevant tradeoff between efficiency and fairness among multiple service providers.

INDEX TERMS Distributed mobile cloud computing, computation offload, cooperative game theory, coalitional value solutions, cloud resource sharing, fairness.

I. INTRODUCTION

Due to extensive growth in the number of Internet-of-Things (IoT) devices, six generation (6G) communication systems aim to achieve high spectral and energy efficiency, low latency, and massive connectivity. Especially, IoT devices are predicted to reach 25 billion by the year 2025. Therefore, it is very challenging for the existing multiple process techniques to accommodate such a massive number of IoT devices. To adaptively operate the huge amount of data produced by massive devices, the idea of cloud computing will be an essential component of 6G networks. This means that computing power or software applications can be delivered and circulated over the Internet as a versatile commodity for fast access to services [1], [2].

As a new paradigm for supporting mobile users, cloud computing technology integrates with a mobile environment; it is called as the mobile cloud computing (MCC). The MCC is the delivery of resources and computing powers over the Internet, such that accesses to shared hardware, software, databases, information, and all resources are provided to IoT devices on-demand. By offloading data processing tasks from IoT devices to the MCC server, this paradigm can reduce an execution time of mobile applications and also the energy consumption of IoT devices. In fact, the MCC's ability to provide on demand access to always-on computing utilities has attracted many industry enterprises due to their cost-benefit ratios; it leads to rapid growth of the cloud computing market. However, the variability of IoT devices' demands increases when it comes to their different requests. This situation in the MCC paradigm necessitates to reshape its business model while seeking to improve its dynamic resource scaling capability [3], [4].

Future MCC systems will be based on highly heterogeneous infrastructures. As of today, multiple different MCC service providers have been deployed and proposed to support an emerging wide range of innovative cloud services. Traditionally, centralized infrastructure of MCC platform is

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well studied in many researches. However, such centralized approach may bring several disadvantages, including limited resource sharing, high bandwidth for communications, and potentially high service delay, which is certainly undesirable for time-sensitive applications. It is envisioned that the MCC infrastructure will gradually develop into distributed infrastructures while service providers (SPs) can take advantages of geo-diversity to increase revenue and system performance. This approach has developed a new distributed MCC (DMCC) infrastructure. In the DMCC platform, the cloud resources are also geographically distributed over a wide-area network. If a SP does not have enough resource used for providing on various demand services, other SPs that have unused capacities can make profit by participating in a cooperative coalition, which enables the formation of a pool of DMCC resources to achieve greater scalability and performance. By forming a cloud coalition with other SPs, it can dynamically scale-up the DMCC system's resource capabilities. However, the DMCC system is still in its infancy. In practice, how to optimally share the limited cloud resources still faces many challenges [3]–[6].

Nowadays, the broad range of IoT based applications exhibit high temporal variations of their workload, and require high QoS (Quality of Service) for DMCC services. In order to satisfy the increasingly demanding performance requirements of these applications, we focus on the SPs' cooperation by resource sharing process. In this study, the cooperation of SPs in the DMCC platform is classified into two phase mechanisms; the local and global resource sharing cooperation methods. In the local phase cooperation method, the local coalition of different SPs is formed and work together to share the cloud resources in the same local area. In the global phase cooperation method, the resource sharing happens among geographically distributed cloud resources, which are owned by a specific SP. As a consequence, our local and global cooperation mechanisms can improve the resource utilization under the DMCC system uncertainties. To effectively implement our two-phase cooperation algorithms, key challenges are i) to understand the behaviors of self-regarding SPs in the DMCC platform, and ii) to ensure the fairness among SPs for offloading services. To handle these challenges, we adopt the cooperative game theory to negotiate conflicting SPs' viewpoints and their preferences. Traditionally, the main feature of cooperative game is to ensure a relevant tradeoff between efficiency and fairness.

A. TECHNICAL CONCEPTS

In cooperative games, the most difficult issue is how of gain from cooperation is shared. Usually, there are many natural settings in which players organize themselves into coalitions for the purpose of payoff sharing. This fact is incorporated into the game by a coalition structure, which is an exogenous partition of players into a set of groups. Therefore, the evaluation of players' expectations in the cooperative game is given by a coalitional value. A pioneering study that addresses this problem is that of L. Shapley. He considered to find a solution concept, called *Shapley value*, which is seen as a measure of the average marginal contribution of a player to each and every possible coalition while satisfying efficiency, symmetry, dummy and additivity properties. Even though the *Shapley value* serves as the central solution concept for cooperative coalition games, there is still critique. In this spirit, we introduce and discuss new and novel coalition game methods [7], [8].

In this paper, we adopt the *egalitarian non-individual contribution* (*ENIC*) axiom to share the limited DMCC resources. This feature represents the equal division of the surplus of the total profits, given that each player is already allocated some kind of an individual contribution. Based on the *ENIC* characteristic, the unspecified notion of individual contribution can be chosen to be one of five different ideas. Therefore, five particular versions; the *center of the imputation set value* (*CIS value*), α-*CIS value*, *egalitarian non-separable contribution value* (*ENSC value*), *egalitarian non-pairwise averaged contribution value* (*ENPAC value*), and *egalitarian non-Banzhaf contribution value* (*ENBC value*) are developed by choosing the individual worth, i.e., *CIS value*, the convex combinations of the *CIS* and equal division idea, i.e., α-*CIS value*, the separable contribution, i.e., *ENSC value*, the pairwise-averaged contribution, i.e., *ENPAC value*, and the Banzhaf contribution as the notion of individual contribution, i.e., *ENBC value* [9], [10].

B. MAIN CHALLENGES

According to the coalitional value solutions, we can effectively solve the resource allocation problems in the DMCC platform. By considering different IoT applications and distributed cloud infrastructure, we design a novel two-phase cooperative game model, which can not only be axiomatically characterized but which is also constructive based on the DMCC infrastructure. In the local level process, the different SPs' resources in each base station (BS) are shared according to the ideas of *CIS*, α-*CIS* and *ENSC values*. In the global level process, a SP's cloud resources, which are geographically distributed, are shared based on the concepts of *ENPAC* and *ENBC values*. In addition, heterogeneous IoT applications are categorized into two different types, and they are treated differently based on the service characteristics. During iterative cooperation interactions, we appropriately handle the growing demand of computation offloading requests while leading to an optimized system performance. In detail, the major contributions of this study are summarized as below;

- We investigate the ideas of *CIS*, α-*CIS*, *ENSC*, *ENPAC* and *ENBC values* to design our cloud resource sharing algorithm. By considering the features of DMCC infrastructure, we formulate different cooperative game models to support various computation offloading services.
- In the local level process, each SP divides its computation resource into two parts, which are assigned for

the corresponding service types. This decision process is designed according to the $\alpha-CIS$ *value*.

- And then, individual SPs' cloud resources in the individual BS are locally shared. Through the ideas of *CIS* and *ENSC values*, we can compromise the conflicting views of multiple SPs for different type offloading services.
- In the global level process, each SP's geographically distributed cloud resources are globally shared. To get a rationally desirable solution, the concepts of *ENPAC* and *ENBC values* are adopted to reach a mutual advantage agreement.
- Based on the iterative combination of local and global level processes, we leverage a reciprocal consensus among multiple SPs in a coordinated manner.
- Through simulation analysis over realistic scenarios, we compare the performance of proposed scheme with the existing state-of-the-art computation offloading control protocols. Numerical results confirm that our cooperative method can offer synergistic features under dynamic changing DMCC system environments.

Until now, some cooperative resource allocation schemes have proposed with novel ideas for the DMCC systems. Instead of the existing protocols, the main contribution of our approach lies in the resource allocation formulation with *CIS*, α-*CIS*, *ENSC*, *ENPAC* and *ENBC values*. To the best of our knowledge, this is the first work jointly considering multiple value solutions to adapt dynamic DMCC platform environments. Due to the desirable characteristics of cooperative game theory, our hybrid approach can get a globally desirable DMCC system performance.

II. RELATED WORK

Recently, mobile cloud service has been a popular subject of research, and it is becoming increasingly common. The main research work is focused on the analysis of competitive relations and the distribution of cooperative benefits. The paper [16] presents two workload consolidation techniques - Minimum Power Best Fit Decreasing (MPBFD) and Maximum Capacity Best Fit Decreasing (MCBFD) - for heterogeneous cloud data centers. They intend to provide energy efficiency while ensuring the agreed QoS. Furthermore, two existing techniques, namely, Enhanced-Conscious Task Consolidation (ECTC) and Maximum Utilization (MaxUtil) have been enhanced to improve the energy efficiency and service level agreement awareness. Finally, a detail complexity analysis of each technique is also provided [16].

The paper [17] presents an overview of the computation offloading techniques that are used by different types of mobile cloud application models, and highlights their cost incurring entities and parameters. Using the highlighted parameters, this paper formulates a mathematical model with an effort to include a maximum number of entities so that it can be used for simulation of a large number of mobile cloud application models; it is the first mathematical model that can facilitate to calculate the computation offloading time and energy of the application models [17].

In [18], Ahmed *et al.* highlight the significance of edge computing by providing real-life scenarios that have strict constraint requirements on application response time. They also enable edge computing application engineers and service providers to leverage on the relevant features that can minimize communication and computation latencies while providing edge services to users. The identified requirements can serve as a guide for framework designers in incorporating specific features to efficiently execute the application in the edge computing paradigm. Similarly, these identified challenges highlight future research directions [18].

In [2], Wen *et al.* propose a new scheme to find the right combination of partner cloud services. To satisfy this goal, it provides a new cloud service community partitioning algorithm, which divides the component cloud services into multiple communities according to the execution's record of combined cloud service. By using the community partitioning algorithm, this scheme can divide the component services into their corresponding cooperative communities. In the same community cloud service, there is a cooperative call relationship, which is based on cooperation, and the negotiation risk of the interface is relatively small. Based on this idea, this approach can provide an innovative cloud service selection algorithm for cloud service composition [2].

The *Cooperative Cloud Resource Management* (*CCRM*) scheme studies the computing resource sharing problem to support mobile applications in a mobile cloud computing environment [3]. To maximize the utilization of the cloud resource while optimizing the revenues of SPs, they form a coalition to create a resource pool to share their own resources with each other. Therefore, the cloud resource that is not used by one SP can be used by other SPs to increase the resource utilization. To make best decisions for SPs, linear and stochastic programming formulations, and robust optimization formulation are proposed. And then, the *CCRM* scheme adopts the concept of *Shapley value* to share the revenue generated from the resource pool mechanism [3].

In [5], the *Decentralized and Optimal Resource Cooperation* (*DORC*) scheme studies the SPs' cooperation by resource sharing in the resource allocation problem. In the geo-distributed MCC system, the *DORC* scheme proposes a coalition game approach based on the resource trading model. To improve the resource utilization and system revenue, this scheme exploits the cooperation among SPs in the DMCC infrastructure; the resource-rich SPs are encouraged to lease their available cloud resources to other SPs. By using the coalition game theory and graph theory, the *DORC* scheme can leverage the resource cooperation while optimization with high QoS and satisfying revenues [5].

G. Darzanos et al aim to build a fundamental theory of sharing economy while exploiting the computational capacity resource of SPs, and propose the *Sharing Economy based Cloud Federation* (*SECF*) scheme [6]. First, they introduce innovative federation models and policies for profitable federations that can achieve adequate QoS. And then, each SP is modelled as an M/M/1 queue to guarantee the worst QoS, and mathematical models are formulated for the CSP revenue and cost. The *SECF* scheme adopts two cloud federation algorithms: i) task forwarding (TF) algorithm and ii) capacity sharing (CS) cloud federation algorithm. Under TF, each SP may forward a part of its workload to other federated SPs. Under CS, each SP may share parts of its computational infrastructure with others. In addition, they propose and analyze economic policies for both TF and CS algorithms, and the notion of *Shapley value* is used for the fair distribution of total profit [6].

III. THE PROPOSED DMCC RESOURCE SHARING SCHEME

A. DMCC INFRASTRUCTURE AND TWO-PHASE COOPERATIVE GAME MODEL

A real-world public DMCC system consists of multiple SPs where their resources are geographically distributed in each region. We consider a service region in the DMCC environment; it is covered by wireless BSs. Let there be n number of BSs, which are represented as a set $\mathfrak{B} = \{\mathcal{B}_1, \ldots, \mathcal{B}_n\}$. The set of SPs is denoted by $\mathbb{P} = \{\mathcal{P}_1, \ldots, \mathcal{P}_m\}$, and the set of IoT devices is denoted by $\mathbb{D} = \{\mathcal{D}_1, \ldots, \mathcal{D}_k\}$. IoT devices are distributed across in the DMCC service area, and directly contact with their corresponding BSs. A cloudlet ($\mathcal{C}$) is a mobility-enhanced small-scale cloud datacenter that is located at each BS. In each BS, all SPs install their cloudlets $\left(\mathcal{C}_{\mathcal{P}}^{\mathcal{B}}\right)$. Therefore, each BS has m cloudlets, and each SP install its cloudlets in all BSs where $\mathcal{C}_{\mathcal{P}_j}^{\mathcal{B}_i}$ is the $\mathcal{P}_j$'s cloudlet in the $\mathcal{B}_i$. Let $\mathcal{C}_{\mathcal{B}_i} = \left\{\mathcal{C}_{\mathcal{P}_1}^{\mathcal{B}_i}, \ldots, \mathcal{C}_{\mathcal{P}_m}^{\mathcal{B}_i}\right\}$ be the set of locally clustered cloudlets in the $\mathcal{B}_i$, and $\mathcal{C}_{\mathcal{P}_j} = \left\{\mathcal{C}_{\mathcal{P}_j}^{\mathcal{B}_1}, \ldots, \mathcal{C}_{\mathcal{P}_j}^{\mathcal{B}_n}\right\}$ is the set of globally distributed cloudlets of the $\mathcal{P}_j$; cloudlets in the $\mathcal{C}_{\mathcal{P}}$ are connected through the wired backbone Internet links. Let $\mathfrak{M}_{\mathcal{P}_j}^{\mathcal{B}_i}$ be the computation power of $\mathcal{C}_{\mathcal{P}_j}^{\mathcal{B}_i}$, and the total computation power of $\mathcal{P}_j$ is $\sum_{\mathcal{B}_i \in \mathfrak{B}} \mathfrak{M}_{\mathcal{P}_j}^{\mathcal{B}_i}$. The overview of DMCC system infrastructure is shown in Fig.1 [3], [5], [6].

In our approach, we assume that each individual $\mathcal{C}_{\mathcal{P}}$ serves a large number of computation offloading tasks where each of them may be generated from the $\mathcal{C}_{\mathcal{P}}$'s corresponding IoT devices. Usually, the cloud offloading mechanism for IoT applications combines two separate domains; hard real-time (Hr) and soft real-time (Sr) computing services. Hr service requires a guarantee that all processing is completed within a given time constraint. Therefore, timeliness is a primary measure of correctness. Sr service has a less rigorous notion of time constraint and time delay is not catastrophic. Therefore, it strives for good average-case performance while tolerating a slow response time [11], [12]. According to Hr and Sr service requirements, it is necessary to consider one key question: How to integrate different data services in a unified way to facilitate the DMCC processing while striking an appropriate system performance?

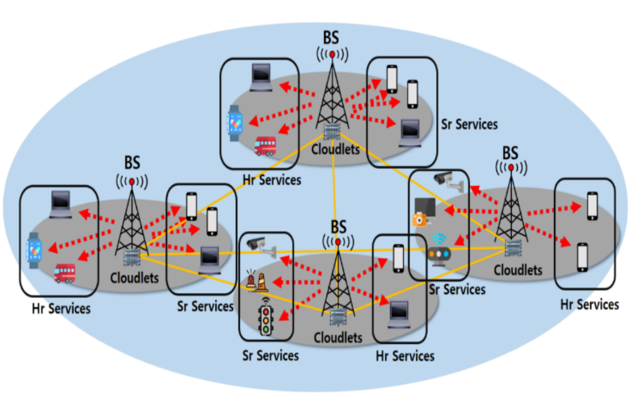

FIGURE 1. The overview of DMCC system platform.

Our two-phase cooperative game model ($\mathbb{G}$) consists of local and global processes to share the DMCC system computation resources. In the local cooperative games $\left(\mathcal{G}_{L,\mathcal{P}}^{\mathcal{B}}, \mathbb{G}_{L}^{\mathcal{B}}\right)$, each cloudlet partitions its computation resource for the Hr and Sr services, and this resource is shared with other cloudlets in the local $\mathcal{B}$. Therefore, the received offloading computation tasks in the $\mathcal{B}$ are adaptively distributed its locally clustered cloudlets. In the global cooperative game $\left(\mathbb{G}_{G}^{\mathcal{P}}\right)$, the geographically distributed cloudlets of a SP work together to support the allocated computation tasks. In a parallel and distributed manner, $\mathcal{G}_{L,\mathcal{P}}^{\mathcal{B}}$, $\mathbb{G}_{L}^{\mathcal{B}}$ and $\mathbb{G}_{G}^{\mathcal{P}}$ act independently and make their decisions toward an appropriate DMCC system performance. Formally, we define our two-phase cooperative game entities, i.e., $\mathbb{G} = \left\{\mathcal{G}_{L,\mathcal{P}}^{\mathcal{B}}, \mathbb{G}_{L}^{\mathcal{B}}, \mathbb{G}_{G}^{\mathcal{P}}\right\} = \left\{\left\{\mathcal{G}_{L,\ \mathcal{P}_j \in \mathbb{P}}^{\mathcal{B}_i \in \mathfrak{B}} | Hr_{\mathcal{B}_i,\mathcal{P}_j}, Sr_{\mathcal{B}_i,\mathcal{P}_j}, \mathcal{U}_{\mathcal{B}_i,\mathcal{P}_j}^{Hr}, \mathcal{U}_{\mathcal{B}_i,\mathcal{P}_j}^{Sr}, \mathcal{S}_{\mathcal{B}_i,\mathcal{P}_j}, \mathfrak{M}_{\mathcal{P}_j}^{\mathcal{B}_i}\right\}, \left\{\mathbb{G}_{L}^{\mathcal{B}_i \in \mathfrak{B}} | \mathcal{S}_{\mathcal{B}_i,\mathcal{P}_j}^{Hr}, \mathcal{S}_{\mathcal{B}_i,\mathcal{P}_j}^{Sr}, \mathcal{C}_{\mathcal{B}_i}, \mathfrak{P}_{\mathcal{B}_i,\mathcal{P}_j}^{Hr}, \mathfrak{P}_{\mathcal{B}_i,\mathcal{P}_j}^{Sr}, U_{L,\mathcal{B}_i}^{Hr,\mathcal{P}_j}, U_{L,\mathcal{B}_i}^{Sr,\mathcal{P}_j}\right\}, \left\{\mathbb{G}_{G}^{\mathcal{P}_j \in \mathbb{P}} | \mathcal{C}_{\mathcal{P}_j}, \mathfrak{U}_{G,\mathcal{P}_j}^{Hr,\mathcal{B}_i}, \mathfrak{U}_{G,\mathcal{P}_j}^{Sr,\mathcal{B}_i}\right\}, T\right\}$:

- In the game $\mathbb{G}$, $\mathcal{G}_{L,\mathcal{P}}^{\mathcal{B}}$ and $\mathbb{G}_{L}^{\mathcal{B}}$ are the local cooperative games in the $\mathcal{B}$; the $\mathcal{G}_{L,\mathcal{P}}^{\mathcal{B}}$ is for service types and the $\mathbb{G}_{L}^{\mathcal{B}}$ is for local cloudlets. $\mathbb{G}_{G}^{\mathcal{P}}$ is the global cooperative game for SPs. $\mathcal{G}_{L,\mathcal{P}}^{\mathcal{B}}$, $\mathbb{G}_{L}^{\mathcal{B}}$ and $\mathbb{G}_{G}^{\mathcal{P}}$ games are mutual and reciprocal interdependent in an interactive manner.
    - In the $\mathcal{G}_{L,\mathcal{P}_j}^{\mathcal{B}_i}$, $Hr_{\mathcal{B}_i,\mathcal{P}_j}$ and $Sr_{\mathcal{B}_i,\mathcal{P}_j}$ represent the offloading Hr and Sr services for the $\mathcal{C}_{\mathcal{P}_j}^{\mathcal{B}_i}$. $Hr_{\mathcal{B}_i,\mathcal{P}_j}$ and $Sr_{\mathcal{B}_i,\mathcal{P}_j}$ are game players, and $\mathcal{U}_{\mathcal{B}_i,\mathcal{P}_j}^{Hr}$, $\mathcal{U}_{\mathcal{B}_i,\mathcal{P}_j}^{Sr}$ are their utility functions, respectively.
    - The $\mathcal{S}_{\mathcal{B}_i,\mathcal{P}_j}$ is the total amount of computation offload for the $\mathcal{C}_{\mathcal{P}_j}^{\mathcal{B}_i}$ where $\mathcal{S}_{\mathcal{B}_i,\mathcal{P}_j} = Hr_{\mathcal{B}_i,\mathcal{P}_j} + Sr_{\mathcal{B}_i,\mathcal{P}_j}$. $\mathfrak{M}_{\mathcal{P}_j}^{\mathcal{B}_i}$ is the computation power of $\mathcal{C}_{\mathcal{P}_j}^{\mathcal{B}_i}$.
- In the $\mathbb{G}_{L}^{\mathcal{B}_i}$, $\mathcal{S}_{\mathcal{B}_i,\mathcal{P}_j}^{Hr}$ and $\mathcal{S}_{\mathcal{B}_i,\mathcal{P}_j}^{Sr}$ are the currently allocated cloud resources for the $Hr_{\mathcal{B}_i,\mathcal{P}_j}$ and $Sr_{\mathcal{B}_i,\mathcal{P}_j}$ in the $\mathcal{C}_{\mathcal{P}_j}^{\mathcal{B}_i}$; they are decided according to the $\mathcal{G}_{L}^{\mathcal{B}_i}$.
    - $\mathcal{C}_{\mathcal{B}_i}$ is the set of locally clustered cloudlets in the $\mathcal{B}_i$, and $\mathfrak{P}_{\mathcal{B}_i,\mathcal{P}_j}^{Hr}$, $\mathfrak{P}_{\mathcal{B}_i,\mathcal{P}_j}^{Sr}$ are the $\mathcal{C}_{\mathcal{P}_j}^{\mathcal{B}_i}$'s currently available computation capacities for $Hr_{\mathcal{B}_i,\mathcal{P}_j}$ and $Sr_{\mathcal{B}_i,\mathcal{P}_j}$, respectively.
    - In the $\mathbb{G}_{L}^{\mathcal{B}_i}$, $\mathcal{C}_{\mathcal{P}_j}^{\mathcal{B}_i} \in \mathcal{C}_{\mathcal{B}_i}$ is a game player, and $U_{L,\mathcal{B}_i}^{Hr,\mathcal{P}_j}$ and $U_{L,\mathcal{B}_i}^{Sr,\mathcal{P}_j}$ are the utility functions of $\mathcal{C}_{\mathcal{P}_j}^{\mathcal{B}_i}$ for $Hr_{\mathcal{B}_i,\mathcal{P}_j}$ and $Sr_{\mathcal{B}_i,\mathcal{P}_j}$, respectively.

- In the $\mathbb{G}_{G}^{\mathcal{P}_j}$, $\mathcal{C}_{\mathcal{P}_j}$ is the set of globally distributed cloudlets of $\mathcal{P}_j$, and $\mathcal{C}_{\mathcal{P}_j}^{\mathcal{B}_i} \in \mathcal{C}_{\mathcal{P}_j}$ is a game player. $\mathfrak{U}_{G,\mathcal{P}_j}^{Hr,\mathcal{B}_i}$, $\mathfrak{U}_{G,\mathcal{P}_j}^{Sr,\mathcal{B}_i}$ are utility functions of $\mathcal{C}_{\mathcal{P}_j}^{\mathcal{B}_i}$ for the $Hr_{\mathcal{B}_i,\mathcal{P}_j}$ and $Sr_{\mathcal{B}_i,\mathcal{P}_j}$, respectively.
- $T = \{t_1, \ldots, t_c, t_{c+1}, \ldots\}$ denotes time period, which is represented by a sequence of time steps.

B. THE BASIC IDEA AND FUNDAMENTAL CONCEPT OF VALUE SOLUTIONS

To characterize the basic concepts of value solutions, we assume a $n-$player game. Let (N, v) be a cooperative $n-$player game with characteristic function where $N = \{1, \ldots, n\}$ is a finite set of players and v: $2^N \rightarrow \mathbb{R}$ is a characteristic function. Coalitions are defined on the power set 2^N of all subsets of N. With every coalition $S \in 2^N$, there is associated the real number $v(S)$, which represents the joint profit that the players in S can achieve due to their cooperative behaviors. For coalition games, the one-point solution concept is called *value*, and its major goal is how to divide the overall profits $v(N)$ among all the players of (N, v). Any value can be interpreted as an allocation rule of the total profit among the players in a game. Mathematically, it is a function Φ that assigns a payoff vector $\Phi(N, v) = (\Phi_i(N, v))_{i \in N}$ to every game (N, v) where $\sum_{i \in N} \Phi_i(N, v) = v(N)$ to meet the efficiency principle. Finally, $\Phi_i(N, v)$ is the value of player i in the game (N, v); it represents the player i's gain from participating in the coalitional game [9], [10].

The *CIS value* assigns to every player its singleton worth, and then distributes the remaining worth of the grand coalition equally among all players. It concerns only about the worth of individuals and the grand coalition since the grand coalition sometimes forms directly from singletons, without other intermediate coalitions forming. To reconcile the major economic allocation ideas, i.e., egalitarianism and marginalism, the *CIS value* $\left(\Phi_{i \in N}^{CIS}(N, v)\right)$ is formally defined as follows [10], [13];

$$\Phi_i^{CIS}(N, v) := v(\{i\}) + \left(\frac{1}{n} \times \left[v(N) - \sum_{j \in N} v(\{j\})\right]\right) \quad \text{s.t., } i \in N \tag{1}$$

The *α-CIS value* considers the convex combinations of the *CIS value* and the equal division solution. Therefore, the *α-CIS value* can be represented as a payoff first assigning to every player only a fraction α of his individual worth, and then distributing the remaining worth of the grand coalition equally among all players. The *α-CIS value*, i.e., $\Phi_{i \in N}^{\alpha-CIS}(N, v)$, is given by [13].

$$\begin{aligned} \Phi_i^{\alpha-CIS}(N, v) &:= \alpha \cdot v(\{i\}) \\ &\quad + \left(\frac{1}{n} \times \left[v(N) - \alpha \cdot \sum_{j \in N} v(\{j\})\right]\right) \\ \text{s.t., } \alpha &\in [0, 1] \end{aligned} \tag{2}$$

The *ENSC value* is the dual of the *CIS value*, and has several dual properties. Therefore, it assigns to every player in a game its marginal contribution to the grand coalition and distributes the positive or negative remainder equally among the players. Mathematically, the *ENSC value*, i.e., $\Phi_{i \in N}^{ENSC}(N, v)$, is defined as follows [10], [14];

$$\begin{aligned} \Phi_{i \in N}^{ENSC}(N, v) &:= \psi_i(N, v) \\ &\quad + \left(\frac{1}{n} \times \left[v(N) - \sum_{j \in N} \psi_j(N, v)\right]\right) \\ \text{s.t., } \psi_i(N, v) &= (v(N) - v(N - \{i\})) \text{ and } i \in N \end{aligned} \tag{3}$$

The *ENPAC value* is basically composed of pairwise contributions with respect to the formation of the grand coalition. According to pairs of players, it involves two stages. First, the pairwise-average contribution of a player is estimated. For example, the player i's pairwise-average contribution is obtained by averaging over all other player $j \in N \setminus \{i\}$. Second, the resulting allocation to the player i is obtained by the egalitarian division of the surplus of the overall profits after each player is conceded to get his pairwise-average contribution. That is the remaining amount of the overall profits is equally distributed to all players of the game. The *ENPAC value*, i.e., $\Phi_{i \in N}^{ENPAC}(N, v)$, is given by [9], [10].

$$\begin{aligned} \Phi_{i \in N}^{ENPAC}(N, v) &:= \gamma_i(N, v) \\ &\quad + \left(\frac{1}{n} \times \left[v(N) - \sum_{j \in N} \gamma_j(N, v)\right]\right) \\ \text{s.t., } \gamma_i(N, v) &= \left(v(N) - \left(\frac{1}{n-2} \times \sum_{j \in N \setminus \{i\}} v(N - \{i, j\})\right)\right) \end{aligned} \tag{4}$$

Usually, the Banzhaf contribution (Γ) of the player is interpretable as the average of all the player's marginal contributions to participate in the game. By assuming that an individual contribution of any player is the Banzhaf contribution, the *ENBC value*, i.e., $\Phi_{i \in N}^{ENBC}(N, v)$, is defined as follows [9];

$$\begin{aligned} \Phi_{i \in N}^{ENBC}(N, v) &:= \Gamma_i(N, v) \\ &\quad + \left(\frac{1}{n} \times \left[v(N) - \sum_{j \in N} \Gamma_j(N, v)\right]\right) \\ \text{s.t., } \Gamma_i(N, v) &= \frac{1}{2^{n-1}} \times \left(\sum_{S \subseteq N \setminus \{i\}} (v(S \cup \{i\}) - v(S))\right) \end{aligned} \tag{5}$$

The *CIS*, *α-CIS*, *ENSC*, *ENPAC* and *ENBC values* respectively satisfy the *relatively invariant under strategic equivalence* (***RISE***) and *equal treatment property* (***ETP***) [9].

- ***RISE*** **:** for all games (N, ω) and (N, v), $\Phi(N, \omega) = \alpha \cdot \Phi(N, v) + \beta$ while satisfying $\omega = \alpha \cdot v + \beta$ for some $\alpha > 0$ and $\beta \in \mathbb{R}^N$.

- ***ETP*** : for any substitutes $i, j\in N$ in a game (N, v), $\Phi_i(N, v) = \Phi_j(N, v)$.

C. THE LOCAL AND GLOBAL COOPERATIVE GAMES IN THE DMCC PLATFORM

At each time $t_c\in T$, IoT devices in $\mathbb{D}$ offload independently their computation tasks to the corresponding SP. Their tasks can be categorized into Hr and Sr services. In each $\mathcal{B}\in\mathfrak{B}$, multiple SPs coexist, and we mediate inter and intra SP interactions to support DMCC computation offloading services. Usually, resource sharing problem is analogous to the bankruptcy problem. A bankruptcy problem is a pair $(E, \boldsymbol{c})$; E represents the total value of the estate and $\boldsymbol{c} = (c_1, \ldots, c_n)$ is the vector of the creditors' claims where $0 < E < \sum_{i=1}^{n} c_i$. Traditionally, to estimate value solutions, the characteristic function $v(S)$ for the coalition S is defined based on the bankruptcy model [15].

$$v(S) = \max\left(0, E - \sum_{i\in S} c_i\right) \tag{6}$$

In the proposed scheme, we design a new two-phase DMCC resource sharing scheme. At first, in the local level, the total computation amount of $\mathcal{C}_{\mathcal{P}}^{\mathcal{B}}$ is divided two parts; one part is for the Hr service, and the other part is for the Sr service. For the $\mathcal{G}_{L,\mathcal{P}_j}^{\mathcal{B}_i}$, $Hr_{\mathcal{B}_i,\mathcal{P}_j}$ and $Sr_{\mathcal{B}_i,\mathcal{P}_j}$ are game players and their utility functions, i.e., $\mathcal{U}^{Hr}_{\mathcal{B}_i,\mathcal{P}_j}(\cdot)$ and $\mathcal{U}^{Sr}_{\mathcal{B}_i,\mathcal{P}_j}(\cdot)$, are defined as follows;

$$\begin{cases} \mathcal{U}^{Hr}_{\mathcal{B}_i,\mathcal{P}_j}\left(R^{Hr}_{\mathcal{B}_i,\mathcal{P}_j}, \mathcal{S}^{Hr}_{\mathcal{B}_i,\mathcal{P}_j}, \mathfrak{M}^{\mathcal{B}_i}_{\mathcal{P}_j}\right) \\ = \dfrac{\theta}{\eta + exp\left(\xi \times \dfrac{\min\left(R^{Hr}_{\mathcal{B}_i,\mathcal{P}_j}, \mathcal{S}^{Hr}_{\mathcal{B}_i,\mathcal{P}_j}\right)}{\mathfrak{M}^{\mathcal{B}_i}_{\mathcal{P}_j}}\right)} \\ \mathcal{U}^{Sr}_{\mathcal{B}_i,\mathcal{P}_j}\left(R^{Sr}_{\mathcal{B}_i,\mathcal{P}_j}, \mathcal{S}^{Sr}_{\mathcal{B}_i,\mathcal{P}_j}, \mathfrak{M}^{\mathcal{B}_i}_{\mathcal{P}_j}\right) \\ = \dfrac{\theta}{\eta + \left(\varepsilon \times exp\left(\dfrac{\min\left(R^{Sr}_{\mathcal{B}_i,\mathcal{P}_j}, \mathcal{S}^{Sr}_{\mathcal{B}_i,\mathcal{P}_j}\right)}{\mathfrak{M}^{\mathcal{B}_i}_{\mathcal{P}_j}}\right)\right)} \end{cases} \tag{7}$$

where $R^{Hr}_{\mathcal{B}_i,\mathcal{P}_j}$ and $R^{Sr}_{\mathcal{B}_i,\mathcal{P}_j}$ $\left(or\ \mathcal{S}^{Hr}_{\mathcal{B}_i,\mathcal{P}_j} \text{and} \mathcal{S}^{Sr}_{\mathcal{B}_i,\mathcal{P}_j}\right)$ are the requested amounts (*or* currently allocating cloud computing resource) for $Hr_{\mathcal{B}_i,\mathcal{P}_j}$ and $Sr_{\mathcal{B}_i,\mathcal{P}_j}$, respectively. η, θ, ξ and ε are the adjustment parameters for the $\mathcal{U}_{\mathcal{B}_i,\mathcal{P}_j}(\cdot)$. To decide the $\mathcal{S}^{Hr}_{\mathcal{B}_i,\mathcal{P}_j}$ and $\mathcal{S}^{Sr}_{\mathcal{B}_i,\mathcal{P}_j}$ values for the $\mathcal{C}^{\mathcal{B}_i}_{\mathcal{P}_j}$, we adopt the idea of *$\alpha$-CIS value*. Based on the bankruptcy problem, we can get the $v(S)$ value where $c_{Hr} = \mathcal{U}^{Hr}_{\mathcal{B}_i,\mathcal{P}_j}\left(\mathcal{S}^{Hr}_{\mathcal{B}_i,\mathcal{P}_j} = R^{Hr}_{\mathcal{B}_i,\mathcal{P}_j}\right)$, $c_{Sr} = \mathcal{U}^{Sr}_{\mathcal{B}_i,\mathcal{P}_j}\left(\mathcal{S}^{Sr}_{\mathcal{B}_i,\mathcal{P}_j} = R^{Sr}_{\mathcal{B}_i,\mathcal{P}_j}\right)$ and $E = \vartheta \times (c_{Hr} + c_{Sr})$; ϑ is an adjustment factor to estimate the grand coalition value. According to (2), the $\mathcal{S}^{Hr}_{\mathcal{B}_i,\mathcal{P}_j}$ and $\mathcal{S}^{Sr}_{\mathcal{B}_i,\mathcal{P}_j}$ are decided such as $\mathcal{S}^{Hr}_{\mathcal{B}_i,\mathcal{P}_j} = \Phi^{\alpha-CIS}_{Hr_{\mathcal{B}_i,\mathcal{P}_j}}$ and $\mathcal{S}^{Sr}_{\mathcal{B}_i,\mathcal{P}_j} = \Phi^{\alpha-CIS}_{Sr_{\mathcal{B}_i,\mathcal{P}_j}}$.

$$\begin{aligned} \Phi^{\alpha-CIS}_{i\in\mathcal{N}}(\mathcal{N}, v) &:= \alpha \cdot v(\{i\}) \\ &\quad + \left(\frac{1}{2} \times \left[v(\mathcal{N}) - \alpha \cdot \sum_{j\in\mathcal{N}, i\neq j} v(\{j\})\right]\right) \\ \text{s.t., } \mathcal{N} &= \left\{Hr_{\mathcal{B}_i,\mathcal{P}_j}, Sr_{\mathcal{B}_i,\mathcal{P}_j}\right\} \text{ and} \\ \alpha &= \mathbf{max}\left(\frac{R^{Hr}_{\mathcal{B}_i,\mathcal{P}_j}}{R^{Hr}_{\mathcal{B}_i,\mathcal{P}_j} + R^{Sr}_{\mathcal{B}_i,\mathcal{P}_j}}, \sigma\right) \end{aligned} \tag{8}$$

where $0\leq\alpha\leq 1$ and σ is the priority factor. For the $\mathbb{G}_L^{\mathcal{B}_i}$ game, each cloudlet in the $\mathcal{B}_i$, i.e., $\mathcal{C}^{\mathcal{B}_i}_{\mathcal{P}_j}\in\mathcal{C}_{\mathcal{B}_i}$, is a game player, and the $\mathbb{G}_L^{\mathcal{B}_i}$ game consists of two subgames; one is for the Hr service and the other is for the Sr service. In the $\mathbb{G}_L^{\mathcal{B}_i}$, $\mathcal{C}^{\mathcal{B}_i}_{\mathcal{P}_j}$'s utility function for $Hr_{\mathcal{B}_i,\mathcal{P}_j}$, i.e., $U^{Hr,\mathcal{P}_j}_{L,\mathcal{B}_i}(\cdot)$, is defined as follows;

$$\begin{aligned} &U^{Hr,\mathcal{P}_j}_{L,\mathcal{B}_i}\left(\mathfrak{P}^{Hr}_{\mathcal{B}_i,\mathcal{P}_j}, \mathcal{S}^{Hr}_{\mathcal{B}_i,\mathcal{P}_j}, A^{Hr}_{\mathcal{B}_i,\mathcal{P}_j}\right) \\ &= \left(\left(\gamma_{Hr} + \frac{\mathfrak{P}^{Hr}_{\mathcal{B}_i,\mathcal{P}_j}}{\mathcal{S}^{Hr}_{\mathcal{B}_i,\mathcal{P}_j}}\right) \times \log\left(\frac{A^{Hr}_{\mathcal{B}_i,\mathcal{P}_j}}{\mathcal{S}^{Hr}_{\mathcal{B}_i,\mathcal{P}_j}} + \omega_{Hr}\right)\right) \end{aligned} \tag{9}$$

where $A^{Hr}_{\mathcal{B}_i,\mathcal{P}_j}$ is the currently allocating $\mathcal{C}^{\mathcal{B}_i}_{\mathcal{P}_j}$'s cloud resource for the $Hr_{\mathcal{B}_i,\mathcal{P}_j}$ and γ_{Hr}, ω_{Hr} are the adjustment parameters for the $U^{Hr,\mathcal{P}_j}_{L,\mathcal{B}_i}(\cdot)$. For the Sr service in the $\mathbb{G}_L^{\mathcal{B}_i}$ game, the $\mathcal{C}^{\mathcal{B}_i}_{\mathcal{P}_j}$'s utility function for the $Sr_{\mathcal{B}_i,\mathcal{P}_j}$, i.e., $U^{Sr,\mathcal{P}_j}_{L,\mathcal{B}_i}(\cdot)$, is defined as the same manner as $U^{Hr,\mathcal{P}_j}_{L,\mathcal{B}_i}(\cdot)$; only $\mathcal{S}^{Hr}_{\mathcal{B}_i,\mathcal{P}_j}$, $A^{Hr}_{\mathcal{B}_i,\mathcal{P}_j}$,$\gamma_{Hr}$ and ω_{Hr} are replaced by $\mathcal{S}^{Sr}_{\mathcal{B}_i,\mathcal{P}_j}$, $A^{Sr}_{\mathcal{B}_i,\mathcal{P}_j}$,$\gamma_{Sr}$ and ω_{Sr}, respectively. The $A^{Sr}_{\mathcal{B}_i,\mathcal{P}_j}$ is the currently allocating $\mathcal{C}^{\mathcal{B}_i}_{\mathcal{P}_j}$'s cloud resource for the $Sr_{\mathcal{B}_i,\mathcal{P}_j}$, and γ_{Sr}, ω_{Sr} are the adjustment parameters for the $U^{Sr,\mathcal{P}_j}_{L,\mathcal{B}_i}(\cdot)$. To decide the $A^{Hr}_{\mathcal{B}_i,\mathcal{P}_j}$ value, we adopt the idea of *CIS value*, and we can get the $v(S)$ value where $c_{\mathcal{C}^{\mathcal{B}_i}_{\mathcal{P}_j}} = U^{Hr,\mathcal{P}_j}_{L,\mathcal{B}_i}\left(A^{Hr}_{\mathcal{B}_i,\mathcal{P}_j} = \mathcal{S}^{Hr}_{\mathcal{B}_i,\mathcal{P}_j}\right)$ and $E = \vartheta \times \left(\sum_{\mathcal{C}^{\mathcal{B}_i}_{\mathcal{P}_k}\in\mathcal{C}_{\mathcal{B}_i}} U^{Hr,\mathcal{P}_k}_{L,\mathcal{B}_i}\left(A^{Hr}_{\mathcal{B}_i,\mathcal{P}_k} = \mathcal{S}^{Hr}_{\mathcal{B}_i,\mathcal{P}_k}\right)\right)$. According to (1), the $A^{Hr}_{\mathcal{B}_i,\mathcal{P}_j}$ value is decided such as $A^{Hr}_{\mathcal{B}_i,\mathcal{P}_j} = \Phi^{CIS}_{\mathcal{C}^{\mathcal{B}_i}_{\mathcal{P}_j}}(\mathcal{C}_{\mathcal{B}_i}, v)$.

$$\begin{aligned} &\Phi^{CIS}_{\mathcal{C}^{\mathcal{B}_i}_{\mathcal{P}_j}}(\mathcal{C}_{\mathcal{B}_i}, v) \\ &:= v\left(\left\{\mathcal{C}^{\mathcal{B}_i}_{\mathcal{P}_j}\right\}\right) + \left(\frac{1}{\left\|\mathcal{C}_{\mathcal{B}_i}\right\|}\right. \\ &\quad \left. \times \left[v(\mathcal{C}_{\mathcal{B}_i}) - \sum_{\mathcal{C}^{\mathcal{B}_i}_{\mathcal{P}_k}\in\mathcal{C}_{\mathcal{B}_i}} v\left(\left\{\mathcal{C}^{\mathcal{B}_i}_{\mathcal{P}_k}\right\}\right)\right]\right) \end{aligned} \tag{10}$$

where $\left\|\mathcal{C}_{\mathcal{B}_i}\right\|$ is the cardinality of $\mathcal{C}_{\mathcal{B}_i}$. To decide the $A^{Sr}_{\mathcal{B}_i,\mathcal{P}_j}$ value, we adopt the idea of *ENSC value*, and we can get the

$v(S)$ value as the same manner as the *CIS value*. According to (3), the $A^{Sr}_{\mathcal{B}_i,\mathcal{P}_j}$ value is decided such as $A^{Sr}_{\mathcal{B}_i,\mathcal{P}_j} = \Phi^{ENSC}_{\mathcal{C}^{\mathcal{B}_i}_{\mathcal{P}_j}}\left(\mathcal{C}_{\mathcal{B}_i}, v\right)$.

$$\begin{aligned}\Phi^{ENSC}_{\mathcal{C}^{\mathcal{B}_i}_{\mathcal{P}_j}}\left(\mathcal{C}_{\mathcal{B}_i}, v\right) &:= \psi_{\mathcal{C}^{\mathcal{B}_i}_{\mathcal{P}_j}}\left(\mathcal{C}_{\mathcal{B}_i}, v\right) \\ &\quad + \left(\frac{1}{\left\|\mathcal{C}_{\mathcal{B}_i}\right\|} \times \left[v\left(\mathcal{C}_{\mathcal{B}_i}\right) \right.\right. \\ &\quad \left.\left. - \sum_{\mathcal{C}^{\mathcal{B}_i}_{\mathcal{P}_k} \in \mathcal{C}_{\mathcal{B}_i}} \psi_{\mathcal{C}^{\mathcal{B}_i}_{\mathcal{P}_k}}\left(\mathcal{C}_{\mathcal{B}_i}, v\right)\right]\right) \\ \text{s.t., } \psi_{\mathcal{C}^{\mathcal{B}_i}_{\mathcal{P}_j}}\left(\mathcal{C}_{\mathcal{B}_i}, v\right) &= \left(v\left(\mathcal{C}_{\mathcal{B}_i}\right) - v\left(\mathcal{C}_{\mathcal{B}_i} - \left\{\mathcal{C}^{\mathcal{B}_i}_{\mathcal{P}_j}\right\}\right)\right)\end{aligned} \tag{11}$$

For the $\mathbb{G}^{\mathcal{P}_j}_{G}$ game, globally distributed cloudlets of $\mathcal{C}^{\mathcal{B}_i \in \mathfrak{B}}_{\mathcal{P}_j}$ in $\mathcal{C}_{\mathcal{P}_j}$ are game players. The $\mathcal{C}^{\mathcal{B}_i}_{\mathcal{P}_j}$'s utility functions for the *Hr* and *Sr* services, i.e., $\mathfrak{U}^{Hr,\mathcal{B}_i}_{G,\mathcal{P}_j}(\cdot)$ and $\mathfrak{U}^{Sr,\mathcal{B}_i}_{G,\mathcal{P}_j}(\cdot)$, are defined as follows;

$$\begin{cases} \mathfrak{U}^{Hr,\mathcal{B}_i}_{G,\mathcal{P}_j}\left(\mathfrak{P}^{Hr}_{\mathcal{B}_i,\mathcal{P}_j}, \mathfrak{P}^{Sr}_{\mathcal{B}_i,\mathcal{P}_j}, A^{Hr}_{\mathcal{B}_i,\mathcal{P}_j}, a^{Hr}_{\mathcal{B}_i,\mathcal{P}_j}\right) \\ \quad = \exp\left(\dfrac{\mathbf{min}\left(\left(\mathfrak{P}^{Hr}_{\mathcal{B}_i,\mathcal{P}_j} + \mathfrak{P}^{Sr}_{\mathcal{B}_i,\mathcal{P}_j}\right), a^{Hr}_{\mathcal{B}_i,\mathcal{P}_j}\right)}{A^{Hr}_{\mathcal{B}_i,\mathcal{P}_j}}\right) - \zeta \\ \mathfrak{U}^{Sr,\mathcal{B}_i}_{G,\mathcal{P}_j}\left(\mathfrak{P}^{Sr}_{\mathcal{B}_i,\mathcal{P}_j}, A^{Sr}_{\mathcal{B}_i,\mathcal{P}_j}, a^{Sr}_{\mathcal{B}_i,\mathcal{P}_j}\right) \\ = \mu^{\left(\frac{\mathbf{min}\left(\mathfrak{P}^{Sr}_{\mathcal{B}_i,\mathcal{P}_j}, a^{Sr}_{\mathcal{B}_i,\mathcal{P}_j}\right)}{A^{Sr}_{\mathcal{B}_i,\mathcal{P}_j}}\right)} - \zeta \end{cases} \tag{12}$$

where $a^{Hr}_{\mathcal{B}_i,\mathcal{P}_j}$ and $a^{Sr}_{\mathcal{B}_i,\mathcal{P}_j}$ are the currently allocating $\mathcal{C}^{\mathcal{B}_i}_{\mathcal{P}_j}$'s cloud resources for the *Hr* and *Sr* services, respectively. ζ, μ are the adjustment parameters for the $\mathfrak{U}_{G,\mathcal{P}}(\cdot)$. To decide the $a^{Hr}_{\mathcal{B}_i,\mathcal{P}_j}$ value, we adopt the idea of *ENPAC value*, and the $v(S)$ value is estimated as $c_{\mathcal{C}^{\mathcal{B}_i}_{\mathcal{P}_j}} = \mathfrak{U}^{Hr,\mathcal{B}_i}_{G,\mathcal{P}_j}\left(a^{Hr}_{\mathcal{B}_i,\mathcal{P}_j} = \left(\mathfrak{P}^{Hr}_{\mathcal{B}_i,\mathcal{P}_j} + \mathfrak{P}^{Sr}_{\mathcal{B}_i,\mathcal{P}_j}\right)\right)$ and $E = \vartheta \times \left(\sum_{\mathcal{C}^{\mathcal{B}_k}_{\mathcal{P}_j} \in \mathcal{C}_{\mathcal{P}_j}} \mathfrak{U}^{Hr,\mathcal{B}_k}_{G,\mathcal{P}_j}\left(a^{Hr}_{\mathcal{B}_k,\mathcal{P}_j} = \left(\mathfrak{P}^{Hr}_{\mathcal{B}_k,\mathcal{P}_j} + \mathfrak{P}^{Sr}_{\mathcal{B}_k,\mathcal{P}_j}\right)\right)\right)$. According to (4), the $a^{Hr}_{\mathcal{B}_i,\mathcal{P}_j}$ value is decided as $a^{Hr}_{\mathcal{B}_i,\mathcal{P}_j} = \Phi^{ENPAC}_{\mathcal{C}^{\mathcal{B}_i}_{\mathcal{P}_j}}\left(\mathcal{C}_{\mathcal{P}_j}, v\right)$.

$$\begin{aligned}&\Phi^{ENPAC}_{\mathcal{C}^{\mathcal{B}_i}_{\mathcal{P}_j}}\left(\mathcal{C}_{\mathcal{P}_j}, v\right) \\ &\quad := \gamma_{\mathcal{C}^{\mathcal{B}_i}_{\mathcal{P}_j}}\left(\mathcal{C}_{\mathcal{P}_j}, v\right) + \left(\frac{1}{\left\|\mathcal{C}_{\mathcal{P}_j}\right\|}\right. \\ &\qquad \left. \times \left[- \sum_{\mathcal{C}^{\mathcal{B}_k}_{\mathcal{P}_j} \in \mathcal{C}_{\mathcal{P}_j}}^{v\left(\mathcal{C}_{\mathcal{P}_j}\right)} \gamma_{\mathcal{C}^{\mathcal{B}_k}_{\mathcal{P}_j}}\left(\mathcal{C}_{\mathcal{P}_j}, v\right)\right]\right) \\ &\text{s.t. , } \gamma_{\mathcal{C}^{\mathcal{B}_i}_{\mathcal{P}_j}}\left(\mathcal{C}_{\mathcal{P}_j}, v\right) \\ &\quad = \left(v\left(\mathcal{C}_{\mathcal{P}_j}\right) - \left(\frac{1}{\left\|\mathcal{C}_{\mathcal{P}_j}\right\| - 2}\right.\right. \\ &\qquad \left.\left. \times \sum_{\mathcal{C}^{\mathcal{B}_k}_{\mathcal{P}_j} \in N \setminus \left\{\mathcal{C}^{\mathcal{B}_i}_{\mathcal{P}_j}\right\}} v\left(\mathcal{C}_{\mathcal{P}_j} - \left\{\mathcal{C}^{\mathcal{B}_i}_{\mathcal{P}_j}, \mathcal{C}^{\mathcal{B}_k}_{\mathcal{P}_j}\right\}\right)\right)\right)\end{aligned} \tag{13}$$

To decide the $a^{Sr}_{\mathcal{B}_i,\mathcal{P}_j}$ value of $\mathcal{C}^{\mathcal{B}_i}_{\mathcal{P}_j}$, we adopt the idea of *ENBC value*, and we can get the $v(S)$ value where $c_{\mathcal{C}^{\mathcal{B}_i}_{\mathcal{P}_j}} = \mathfrak{U}^{Sr,\mathcal{B}_i}_{G,\mathcal{P}_j}\left(a^{Sr}_{\mathcal{B}_i,\mathcal{P}_j} = \mathfrak{P}^{Sr}_{\mathcal{B}_i,\mathcal{P}_j}\right)$ and $E = \vartheta \times \left(\sum_{\mathcal{C}^{\mathcal{B}_k}_{\mathcal{P}_j} \in \mathcal{C}_{\mathcal{P}_j}} \mathfrak{U}^{Sr,\mathcal{B}_k}_{G,\mathcal{P}_j}\left(a^{Sr}_{\mathcal{B}_k,\mathcal{P}_j} = \mathfrak{P}^{Sr}_{\mathcal{B}_k,\mathcal{P}_j}\right)\right)$. According to (5), the $a^{Sr}_{\mathcal{B}_i,\mathcal{P}_j}$ value is decided as $a^{Sr}_{\mathcal{B}_i,\mathcal{P}_j} = \Phi^{ENBC}_{\mathcal{C}^{\mathcal{B}_i}_{\mathcal{P}_j}}\left(\mathcal{C}_{\mathcal{P}_j}, v\right)$.

$$\begin{aligned}&\Phi^{ENBC}_{\mathcal{C}^{\mathcal{B}_i}_{\mathcal{P}_j}}\left(\mathcal{C}_{\mathcal{P}_j}, v\right) \\ &\quad := \Gamma_{\mathcal{C}^{\mathcal{B}_i}_{\mathcal{P}_j}}\left(\mathcal{C}_{\mathcal{P}_j}, v\right) + \left(\frac{1}{\left\|\mathcal{C}_{\mathcal{P}_j}\right\|}\right. \\ &\qquad \left. \times \left[v\left(\mathcal{C}_{\mathcal{P}_j}\right) - \sum_{\mathcal{C}^{\mathcal{B}_k}_{\mathcal{P}_j} \in \mathcal{C}_{\mathcal{P}_j}} \Gamma_{\mathcal{C}^{\mathcal{B}_k}_{\mathcal{P}_k}}\left(\mathcal{C}_{\mathcal{P}_j}, v\right)\right]\right) \\ &\text{s.t. , } \Gamma_{\mathcal{C}^{\mathcal{B}_i}_{\mathcal{P}_j}}(N, v) \\ &\quad = \frac{1}{2^{\left(\left\|\mathcal{C}_{\mathcal{P}_j}\right\| - 1\right)}} \\ &\qquad \times \left(\sum_{S \subseteq \mathcal{C}_{\mathcal{P}_j} \setminus \left\{\mathcal{C}^{\mathcal{B}_i}_{\mathcal{P}_j}\right\}} \left(v\left(S \cup \left\{\mathcal{C}^{\mathcal{B}_i}_{\mathcal{P}_j}\right\}\right) - v(S)\right)\right)\end{aligned} \tag{14}$$

D. MAIN STEPS OF OUR PROPOSED DMCC RESOURCE SHARING SCHEME

In this study, we classify different IoT data applications into *Hr* and *Sr* services, and develop a novel local and global level resource sharing algorithms in the DMCC infrastructure. At the local level process, each cloudlet in the BS partitions its resource into two parts, and shares its resource parts with locally neighboring cloudlets. At the global level process, each SP shares its geographically distributed cloudlets' resources. Based on the current DMCC system conditions, we adopt the fundamental ideas of *CIS*, *α-CIS*, *ENSC*, *ENPAC* and *ENBC values* to share the limited cloud resource while ensuring good global properties. Therefore, our coalition game based cooperative approach can achieve a mutually desirable solution while flexibly adapting the dynamic data offloading requests. This feature can maximize the cloud resource efficiency in the DMCC system while achieving the fairness among multiple SPs. The main steps of our proposed scheme can be described as follows:

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

Step 1: At each time epoch t_c, multiple IoT devices independently generate their different type data, and request offloading services their corresponding SPs in the BS.

Step 1: At the local level process, each individual $\mathfrak{C}_{\mathcal{P}}^{\mathcal{B}}$ divides the $\mathfrak{M}_{\mathcal{P}}^{\mathcal{B}}$ into two parts for $Hr_{\mathcal{B},\mathcal{P}}$ and $Sr_{\mathcal{B},\mathcal{P}}$ in the $\mathcal{G}_{L,\mathcal{P}}^{\mathcal{B}}$ game. And then, the locally clustered $\mathfrak{C}_{\mathcal{P}}^{\mathcal{B}}$s in each BS share their cloud resources in the $\mathbb{G}_{L}^{\mathcal{B}}$ game.

Step 1: In the $\mathcal{G}_{L,\mathcal{P}}^{\mathcal{B}}$ game, $Hr_{\mathcal{B},\mathcal{P}}$ and $Sr_{\mathcal{B},\mathcal{P}}$ are game players, and their utility functions are defined in (7). Based on the idea of the α-*CIS value*, $\mathcal{S}_{\mathcal{B},\mathcal{P}}^{Hr}$ and $\mathcal{S}_{\mathcal{B},\mathcal{P}}^{Sr}$ are obtained according to (2),(6) and (8).

Step 1: In the $\mathbb{G}_{L}^{\mathcal{B}}$ game in each BS, the locally clustered $\mathfrak{C}_{\mathcal{P}}^{\mathcal{B}}$s in $\mathfrak{C}_{\mathcal{B}}$ are game players, and their utility functions are defined in (9). By using the concepts of the *CIS* and *ENSC values*, $A_{\mathcal{B},\mathcal{P}}^{Hr}$ and $A_{\mathcal{B},\mathcal{P}}^{Sr}$ are estimated according to (1),(3),(6),(10) and (11).

Step 1: At the global level process, each SP's geographically distributed $\mathfrak{C}_{\mathcal{P}}^{\mathcal{B}}$s in $\mathfrak{C}_{\mathcal{P}}$ are game players, and their utility functions are defined in (12). To get the $a_{\mathcal{B},\mathcal{P}}^{Hr}$ and $a_{\mathcal{B},\mathcal{P}}^{Sr}$ values, the ideas of *ENPAC* and *ENBC values* are adopted according to (4),(5),(6),(13) and (14).

Step 1: In a parallel and distributed manner, $\mathcal{G}_{L}^{\mathcal{B}}$, $\mathbb{G}_{L}^{\mathcal{B}}$ and $\mathbb{G}_{G}^{\mathcal{P}}$ interact with each other and work together in a coordination manner.

Step 1: Constantly, each individual game entities are self-monitoring the current DMCC platform environments, and proceed to Step 2 for the next two-phase cooperative game process.

IV. PERFORMANCE EVALUATION

In this section, we evaluate the effectiveness of our method by conducting extensive experiments. The simulation scenario and environment setup are given below, and parameters settings are described in the Table 1. And then, the numerical results are analyzed via the performance comparison with the existing *CCRM*, *DORC* and *SECF* protocols in [3], [5], [6].

- The simulated DMCC platform consists of four BSs and four SPs where $|\mathfrak{B}| = 4$ and $|\mathbb{P}| = 4$.
- Each SP maintains its cloudlet in each BS. Therefore, $|\mathfrak{C}_{\mathcal{B}}| = |\mathbb{P}|$ and $|\mathfrak{C}_{\mathcal{P}}| = |\mathfrak{B}|$.
- There are 100 IoT devices, and they are evenly distributed in the DMCC system's covering area. Each device is directly contacted to its corresponding cloudlet in the BS.

TABLE 1. System parameters used in the simulation experiments.

Parameter	Value	Description
n	4	the total number of base stations
m	4	the total number of service providers
k	100	the total number of IoT devices
$\mathfrak{M}_{\mathcal{P}}^{\mathcal{B}}$	10 GHz	the computation power of $\mathcal{C}_{\mathcal{P}}^{\mathcal{B}}$
η, θ	1, 1	adjustment parameters for the $\mathcal{U}_{\mathcal{B}}(\cdot)$
ξ, ε	-3, 1.5	control parameter for the $\mathcal{U}_{\mathcal{B}}(\cdot)$
ϑ	0.8	adjustment factor to estimate E
σ	0.2	priority factor for α-*CIS* value
γ_{Hr}, ω_{Hr}	1.2 , 1	adjustment parameter for the $U_{L}^{Hr}(\cdot)$
γ_{Sr}, ω_{Sr}	1 , 1	adjustment parameter for the $U_{L}^{Sr}(\cdot)$
ζ, μ	1 , 2	adjustment parameter for the $\mathfrak{U}(\cdot)$

Applications	Service duration	Offloading computation amount	Preference level
1	15 t	256 MHz	*Sr* service
2	20 t	128 MHz	*Hr* service
3	25 t	256 MHz	*Sr* service
4	30 t	64 MHz	*Hr* service
5	35 t	128 MHz	*Sr* service
6	10 t	256 MHz	*Hr* service

- Individual IoT devices generates its computation offloading data, which are categorized into the *Hr* and *Sr* services. At each time epoch, the generation process for offloading data is Poisson with rate Λ (services/ t), and the range of offered services was varied from 0 to 3.0.
- We assume that the total computation capacity of $\mathfrak{C}_{\mathcal{P}}^{\mathcal{B}}$, i.e., $\mathfrak{M}_{\mathcal{P}}^{\mathcal{B}}$, is 25 GHz; therefore, total computation capacity of each individual SP is 100 GHz.
- Six different kinds of computation offload data are assumed based on their computation resource requirements, service type and service duration times.
- To reduce computation complexity, the amount of cloud resource allocation is specified in terms of minimum units, where one unit-size is 64 MHz in our resource allocation process.
- System performance measures obtained on the basis of 100 simulation runs are plotted as a function of the offered data request load.

A. SYSTEM THROUGHPUT

As shown in Fig.2, we mainly analyze the throughput performance of DMCC system. The x-axis represents the offered computation offloading rates; it is common for other figures, and the y-axis represents the system throughput. It is an important performance criterion for the DMCC system operator. It can be observed that the throughputs of all schemes increase when the offloading rate increases. However, another important observation is that our proposed scheme can

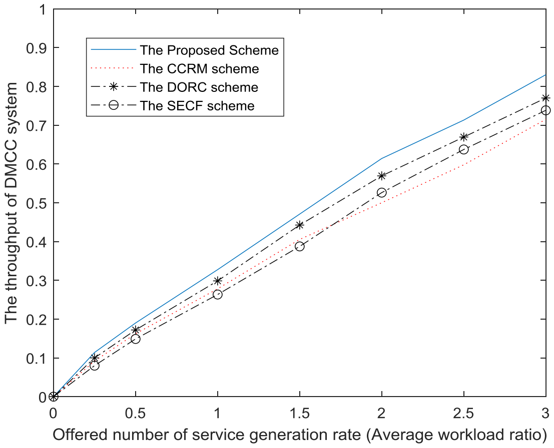

FIGURE 2. **The throughput of DMCC system.**

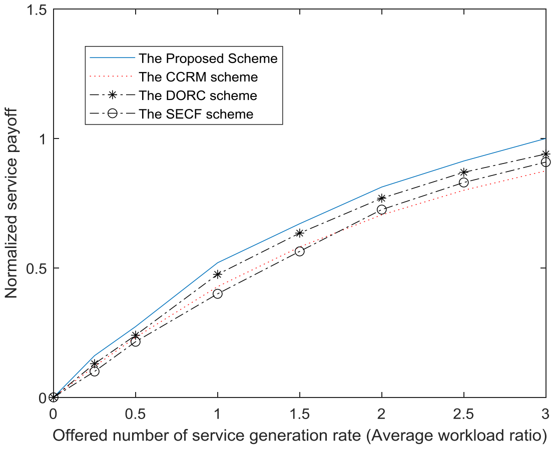

FIGURE 3. **Normalized service payoff.**

maintain a higher system throughput than other existing *CCRM*, *DORC* and *SECF* protocols. This is due to the fact that we can effectively share each individual SP's computation resource based on the coalition based cooperative approach.

B. NORMALIZED SERVICE PAYOFF

Fig.3 compares the normalized service payoff of each protocols. From the viewpoint of individual IoT devices, it is another important performance criterion. In general, the service payoff increases when the DMCC system throughput increases; it is intuitively correct. In our proposed scheme, each cloudlet in the BS can adaptively handle the local offloading requests, and then, individual SPs globally share their distributed computation resources. Therefore, our proposed scheme can achieve a mutually desirable solution by considering the local and global system conditions. The simulation results once again prove that our two-phase resource sharing approach is suitable for the real-world DMCC offloading environment.

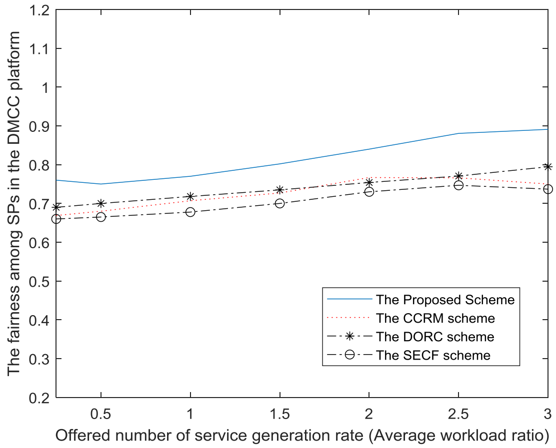

FIGURE 4. **The fairness among SPs in the DMCC platform.**

C. FAIRNESS AMONG SPs IN THE DMCC PLATFORM

The fairness among SPs for offloading services are plotted in Fig.4 for the range of offered request rates. For individual SPs, fairness is a desirable property and interesting control issue. As mentioned earlier, the main characteristic of *CIS*, *α-CIS*, *ENSC*, *ENPAC* and *ENBC values* is to provide a fair-efficient solution for the resource sharing problem. This feature directly implies in the proposed scheme for individual SPs. Therefore, our value solution based approach can achieve the best fairness than the other existing *CCRM*, *DORC* and *SECF* schemes.

V. SUMMARY AND CONCLUSION

The cooperative DMCC paradigm is emerging as an effective solution for the future cloud system. To address the interoperability issues of multiple SPs in the DMCC platform, this paper considers coalition based cooperative game models to support different type cloud services. According to the *CIS*, *α-CIS*, *ENSC*, *ENPAC* and *ENBC values*, our proposed scheme consists of local and global level resource sharing processes. At the local level process, cloud resources in the BS are locally shared according to the ideas of *CIS*, *α-CIS*, *ENSC values*. And then, geographically distributed SPs' resources are effectively shared by using the concepts of *ENPAC* and *ENBC values*. In a parallel and distributed manner, these local and global resource sharing algorithms interact with each other and work together in a coordination manner. With regard to the current computation offloading requests, our proposed scheme has achieved greater and reciprocal advantages under dynamically changeable DMCC system situations. Simulation results indicate that the throughput, service payoff and fairness are improved by about 15%, 15% and 20%, respectively. It is worth noting that our proposed coalition game based cooperative approach is able to efficiently utilize the limited cloud resource while contributing to improve the DMCC system performance.

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

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

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