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Data Offloading in Mobile Edge Computing: A Coalition and Pricing Based Approach

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ABSTRACT Mobile edge computing (MEC) that affords service to the vicinity of mobile devices (MDs) has become a key technology for future network. Offloading big data to the MEC server for preprocessing is an attractive approach of MDs. In this paper, we investigate data offloading from MDs to MEC servers, and a coalitional game-based pricing scheme is proposed. We apply coalitions to arrange data offloading of MDs as well as depict the offloading relationship between MDs and MEC servers. Furthermore, pricing is utilized as the stimuli for the offloading. In the proposed scheme, a scheduled MD in a coalition chooses an MEC server within the same coalition for offloading, and pays the selected MEC server for the MEC service. By analyzing the formulated coalitional non-transferable utility game, theoretical properties are derived and sufficient conditions for the core existence are given. Finally, the utility performances of the proposed scheme are demonstrated by numerical results.

INDEX TERMS Mobile edge computing, offloading, coalitional game, pricing.

I. INTRODUCTION

Mobile edge computing (MEC) enabling low-latency, high-bandwidth, and agile mobile services has attracted much attention in both academia and industry [1]–[3]. MEC is a paradigm that provides cloud services within the vicinity of mobile device via the radio access network. In contrast to the service centralization of mobile cloud computing (MCC), MEC aims to empower the network edge. Since the proximity, MEC has the virtue of low latency, mobile energy saving, privacy and security enhancement, content-awareness. Especially, one advantage is pre-processing of large data at the MEC server before sending it to the cloud. As fusion of wireless communications and mobile computing, MEC is viewed as a key technology of next generation networks, e.g., 5G, Internet of Things (IoT), Internet of Me, Tactile Internet, Social Networks, etc.

As a novel and hot research area, there are some works on MEC. In [4], the offloading from a single mobile device (MD) to multiple edge devices has been investigated under a proposed optimization framework. And the authors focus on the task allocation and computational frequency scaling. In [5], computation offloading together with interference management have been jointly studied under an integrated framework. In [6], performance guaranteed computation

offloading has been investigated for mobile-edge cloud computing. An energy minimizing optimization problem is proposed and solved by apply Karush-Kuhn-Tucker (KKT) conditions. In [7], resource allocation and tasks scheduling in heterogeneous cloud have been studied for delay-bounded MEC. Maximization for the probability of meeting the delay-requirements is proved to be concave and an optimal algorithm is proposed. In [8], Zhang *et al.* have investigated matching problem between the MEC service providers (SPs) and the user equipments (UEs) under a multi-MEC and multi-UE scenario. In [9], joint offloading and computing optimization have been investigated in wireless powered MEC systems. Energy cost minimization of access point is formulated in convex framework and optimal solution in semi-closed form is derived. In [10], the tradeoff between service response time and Quality-of-Result (QoR) has been identified in MEC. A new optimization framework that minimizes app energy consumption and service response time is proposed by jointly optimizing the QoR and the offloading strategy. In [11], an auction-based profit maximization method has been proposed towards the hierarchical MEC. In [12], energy harvesting aided MEC has been investigated, and an online learning algorithm for offloading and auto-scaling is proposed.

Coalitional game theory has been widely applied in design and analysis of wireless communications system especially when cooperation occurs [13]. In [14], a security-aware resource allocation approach of delivering mobile social big data has been proposed by utilizing joint match-coalitional game. In [15], a trust-based hedonic coalitional game has been formulated towards trustworthy multi-cloud services communities, and a three-fold solution is derived thereafter. In [16], A layered coalitional game algorithm is given for hierarchical cooperation in operator-controlled device-to-device (D2D) communications. In [17], by using coalitional game theory, we have studied cooperative transmission in vehicular networks.

Traditional data collection of edge MDs are transferred to the core network directly with high bandwidth cost and latency. Instead, data collection is performed at the edge of the network in MEC. Bandwidth consumption is greatly reduced and latency performance improves. We investigate the data offloading of MEC in the paper. Specifically, data of MDs are transmitted to neighboring MEC servers (offloading from MDs to MEC servers), where preprocessing (e.g., data analytic) is performed, over fading channels. After data preprocessing, the results are sent to the cloud server (over wire channels, e.g., fiber channels). As multiple MDs and multiple MEC servers are considered, the data offloading from MDs to MEC server becomes a challenge problem. *How to schedule multiple MDs' offloading? How to choose the MEC servers for offloading? How to encourage offloading among MDs and MEC servers so as to attain the virtue of MEC?*

Utilizing coalitional game theory and pricing mechanism, we propose a joint coalition-and-pricing based data offloading approach. First, MDs and MEC servers form different coalitions. In each coalition, MDs are scheduled for data offloading to selected MEC server within the same coalition. Selection of MEC servers is closely related to our proposed notion "coverage probability" which shows the availability of MEC servers to MDs. Furthermore, pricing mechanism is utilized to promote cooperation between MDs and MEC servers. In one hand, MDs could gain throughput increase when utilizing MEC server (compared with no MEC). On the other hand, MEC server charges the MDs that choose it as MEC service provider in each data offloading.

The rest of paper is organized as follows. The considered system model and the data offloading scheme are described in Section II. In Section III, a coalitional non-transferable utility (NTU) game is formulated. Next, the game analysis is preformed in Section IV. Numerical results are illustrated in Section V. Finally, Section VI concludes the whole paper and gives future research direction.

II. SYSTEM MODEL AND OFFLOADING SCHEME PROPOSAL

In this section, we first depict the considered scenario. And then the joint coalition and pricing based data offloading scheme is proposed.

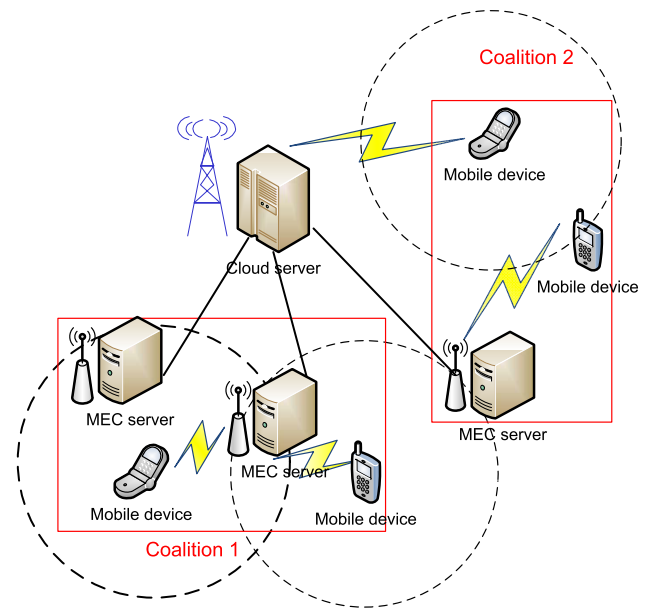


FIGURE 1. MEC network.

A. SYSTEM MODEL

As illustrated in Fig. 1, consider an MEC network consisting of a cloud server, L MEC servers, and K MDs. Data of MDs are transmitted to MEC servers for pre-processing over wireless channels. Thereafter, the results are forwarded to the cloud server. The cloud server is represented as 0. $\mathcal{S} = \{1, \dots, L\}$ and $\mathcal{M} = \{L+1, \dots, L+K\}$ denote the sets of MEC servers and MDs, respectively. Denote the transmit distance of MD $i \in \mathcal{M}$ as d_i . That is to say, within the sphere with radius d_i around MD i (referred to as transmit range), an MEC server could correctly receive the transmitted data. When MEC server $j \in \mathcal{S}$ is in the transmit range of MD i , we call " j covers i ". It is assumed that the coverage relationship does not change during a slot. In the paper, we denote \mathcal{P}_{ji} as the probability that MEC server j covers MD i during a slot. MD $i \in \mathcal{M}$ is active with probability p_i , independently of other MDs, in each slot. When two or more MDs transmit simultaneously, it is referred to as a collision. We assume that the transmissions fail once a collision occurs.

B. COALITION & PRICING BASED DATA OFFLOADING SCHEME

MEC servers and MDs form coalitions to facilitate data offloading. MDs in the same coalition can cooperate to schedule the data offloading, and only one MD can transmit at a slot to avoid interference. MEC servers that are in the same coalition with MD i and cover MD i constitute the feasible MEC server set of MD i . In each coalition, a scheduler chooses an active mobile that can transmit while other active MDs remain silent. When MD i is scheduled to offload at a time-slot, it selects one MEC server from its feasible MEC server set, and sends its data to the the selected MEC server for preprocessing and forwarding. If the feasible MEC server set

is empty, i.e., no MEC server is available, the MD transmits to the cloud server directly (with a lower rate given fixed power) if possible. Then, an MD only transmits to at most one MEC server for each transmission. Furthermore, as no more than one MD is scheduled to transmit at a given time-slot, an MEC server communicates with at the most one MD during a given time-slot. MEC server acts as a helper in data transmission from the MD to the cloud server. When MD i utilizes MEC server j for its transmission, MEC server j charges MD i with price ξ_{ji} per transmission.

When some MDs and MEC servers constitute a coalition, the MDs would share the channel with each other in time division multiple access (TDMA) mode, and they need to pay for the MEC servers. However, the MDs can avoid collision and improve bandwidth efficiency and latency. On the other hand, although there are costs in receiving, processing and forwarding the MDs' data, the MEC servers could achieve revenues by charging the MDs. In a word, both MDs and MEC servers have incentives to form coalitions.

III. COALITIONAL GAME FORMULATION

A coalitional game \mathcal{G} is uniquely defined by the pair (\mathcal{N}, v) , where \mathcal{N} is the set of players, and v is the coalition value quantifying the worth of a coalition in a game. Any non-empty subset of \mathcal{N} is referred to as a coalition. In the paper, players are the MDs and the MEC servers. That is to say, $\mathcal{N} = \mathcal{S} \cup \mathcal{M}$. Denote $S \subseteq \mathcal{N}$ as a coalition, $S_s = S \cap \mathcal{S}$, and $S_m = S \cap \mathcal{M}$. When $S = \mathcal{N}$, it is referred to as the grand coalition.

The per bandwidth data rate increase of MD i with the edge computing of the MEC server j is denoted as Δ_{ij} .¹ Then the per bandwidth rate of MD i when utilizing MEC server j can be expressed as $R_{ij} = r_i + \Delta_{ij}$ with r_i being direct transmission rate to the cloud server under the same power.²

Formally, the scheduler in S is a map $f_S : 2^S \rightarrow S$ such that $f_S(\Psi) \in \Psi$ for all $\Psi \subseteq S$ and $f_S(\Psi) = \emptyset$ iff $\Psi = \emptyset$.

The average effective throughput for MD i can be expressed as

$$T_i(S) = \mathbb{E}_{\Psi} \{1_{f_S(\Psi)=\{i\}}\} (\epsilon_i(S) + \zeta_i(S)) \prod_{j \in \mathcal{M} \setminus S_m} (1 - p_j),$$

where $\mathbb{E}_{\Psi} \{1_{f_S(\Psi)=\{i\}}\}$ denotes the ratio of time-slots that MD i is chosen to transmit. For example, we can assume $f_S(\Psi)$ chooses the minimal element from the set of feasible transmitting MD Ψ . Denote $S_m = \{s_1, \dots, s_{|S_m|}\}$ with $s_1 > \dots > s_{|S_m|}$, then

$$\mathbb{E}_{\Psi} \{1_{f_S(\Psi)=\{s_{|S_m|}\}}\} = p_{s_{|S_m|}} \quad (1)$$

and

$$\mathbb{E}_{\Psi} \{1_{f_S(\Psi)=\{s_k\}}\} = p_{s_k} \prod_{i=k+1}^{|S_m|} (1 - p_{s_i}), \quad k = 1, \dots, |S_m| - 1. \quad (2)$$

¹Since the bandwidth efficiency and latency improves with the edge computing, then the equivalent per bandwidth data rate from the MD to the cloud server increases.

²Specially, when direct transmission is impossible, $r_i = 0$

Since any MEC servers in the feasible set can correctly decode the message, the MD can choose arbitrarily. In the paper, we assume that selection of the MEC server is performed according to a uniform probability distribution. The average data rate for MD i with MEC, $\zeta_i(S)$, is given by

$$\begin{aligned} \zeta_i(S) = & \sum_{j \in S_s} R_{ij} \mathcal{P}_{ji} \prod_{k \neq j \in S_s} (1 - \mathcal{P}_{ki}) \\ & + \sum_{j < k \in S_s} \frac{R_{ij} + R_{ik}}{2} \mathcal{P}_{ji} \mathcal{P}_{ki} \prod_{l \neq j, l \neq k \in S_s} (1 - \mathcal{P}_{li}) \\ & + \sum_{j < k < l \in S_s} \frac{R_{ij} + R_{ik} + R_{il}}{3} \mathcal{P}_{ji} \mathcal{P}_{ki} \mathcal{P}_{li} \\ & \times \prod_{r \neq j, r \neq k, r \neq l \in S_s} (1 - \mathcal{P}_{ri}) + \dots + \frac{\sum_{j \in S_s} R_{ij}}{n} \prod_{j \in S_s} \mathcal{P}_{ji}, \end{aligned}$$

where $n = |S_s|$. If $S_s = \emptyset$, i.e., $n = 0$, $\zeta_i(S) = 0$. The average direct rate without MEC is

$$\epsilon_i(S) = r_i * (1 - \mathcal{P}_i),$$

where

$$\mathcal{P}_i = 1 - \prod_{j \in S_s} (1 - \mathcal{P}_{ji})$$

is the probability that at least one MEC server in the coalition covers MD i . Suppose $\Delta_{ij} = \Delta_i$, i.e., the data increase for MD i is irrelevant to the selection of MEC servers, then $R_{ij} = \mathcal{R}_i$ and the average throughput for MD i can be simplified as

$$T_i(S) = \mathbb{E}_{\Psi} \{1_{f_S(\Psi)=\{i\}}\} (\mathcal{P}_i \mathcal{R}_i + r_i * (1 - \mathcal{P}_i)) \prod_{j \in \mathcal{M} \setminus S_m} (1 - p_j)$$

Remark: If there are active MDs outside S at a given time-slot, at least one MDs outside S transmits simultaneously with the scheduled MD in S no matter how the MDs outside S form coalitions. Thus, there is no collision if and only if (iff) all MDs outside S is inactive.

For MD i , the average payment made to the MEC servers can be given by

$$P_i(S) = \mathbb{E}_{\Psi} \{1_{f_S(\Psi)=\{i\}}\} \chi_i(S)$$

with

$$\begin{aligned} \chi_i(S) = & \sum_{j \in S_s} \xi_{ji} \mathcal{P}_{ji} \prod_{k \neq j \in S_s} (1 - \mathcal{P}_{ki}) \\ & + \sum_{j < k \in S_s} \frac{\xi_{ji} + \xi_{ki}}{2} \mathcal{P}_{ji} \mathcal{P}_{ki} \prod_{l \neq j, l \neq k \in S_s} (1 - \mathcal{P}_{li}) \\ & + \sum_{j < k < l \in S_s} \frac{\xi_{ji} + \xi_{ki} + \xi_{li}}{3} \mathcal{P}_{ji} \mathcal{P}_{ki} \mathcal{P}_{li} \\ & \times \prod_{r \neq j, r \neq k, r \neq l \in S_s} (1 - \mathcal{P}_{ri}) + \dots + \frac{\sum_{j \in S_s} \xi_{ji}}{n} \prod_{j \in S_s} \mathcal{P}_{ji}. \end{aligned}$$

If $n = 0$, $\chi_i(S) = 0$. Assume $\xi_{ji} = \xi_i$, i.e., all the MEC servers set the same price for MD i , then the average payment can be simplified as

$$P_i(S) = \mathbb{E}_\Psi \{1_{f_S(\Psi)=\{i\}}\} \mathcal{P}_i \xi_i.$$

Remark: The MEC server charges the MD once the MDs employs the MEC server for a transmission, it does not take the collisions into account. That is to say, the actions in other coalitions do not influence the charging.

The payoff of MD i is determined by

$$u_i(S) = \alpha_i T_i(S) - \beta_i P_i(S),$$

where α_i and β_i are the weighted values.

For MEC server j in S , the revenue charged from the MDs can be given by

$$R_j(S) = \sum_{i \in S_m} \mathbb{E}_\Psi \{1_{f_S(\Psi)=\{i\}}\} \eta_{ij}(S) \xi_{ji}, \quad (3)$$

where $\eta_{ij}(S)$ is the probability that MD i employs MEC server j for transmission, and it is given by

$$\begin{aligned} \eta_{ij}(S) = & \mathcal{P}_{ji} \left[\prod_{k \neq j \in S_s} (1 - \mathcal{P}_{ki}) \right. \\ & + \frac{1}{2} \sum_{k \neq j \in S_s} \mathcal{P}_{ki} \prod_{l \neq j, l \neq k \in S_r} (1 - \mathcal{P}_{li}) \\ & + \frac{1}{3} \sum_{k < l, k \neq j, l \neq j \in S_s} \mathcal{P}_{ki} \mathcal{P}_{li} \prod_{r \neq j, r \neq k, r \neq l \in S_s} (1 - \mathcal{P}_{ri}) \\ & \left. + \dots + \frac{1}{n} \prod_{k \neq j \in S_s} \mathcal{P}_{ki} \right]. \end{aligned} \quad (4)$$

Assume that MEC server j receives the signal of MD i at cost c_{ji}^r , and the cost of pre-processing data and forwarding results to the cloud server is c_{ji}^f . The average cost of MEC server j can be expressed as

$$C_j(S) = \sum_{i \in S_m} \mathbb{E}_\Psi \{1_{f_S(\Psi)=\{i\}}\} \left[c_{ji}^f \eta_{ij}(S) + \mathcal{P}_{ji} c_{ji}^r \right]. \quad (5)$$

Remark: MEC server j receives the message of MD i once it covers MD i (with probability \mathcal{P}_{ji}), and it pre-processes the message and forwards only when it is selected as the assistant by MD i (with probability $\eta_{ij}(S)$).

The payoff of MEC server j is determined by

$$\tilde{u}_j(S) = \gamma_j R_j(S) - \mu_j C_j(S),$$

where γ_j and μ_j are the weighted values.

Define $v(S) \subseteq \mathbb{R}^{|S_s|+|S_m|}$ be the set of feasible payoff vectors for S , we formulate the considered data offloading problem as a coalitional NTU-game $\mathcal{G} : (\mathfrak{M} \cup \mathfrak{S}, v)$.

IV. COALITIONAL GAME ANALYSIS

In this section, we carry out analytical analysis on the formulated game. First, we present two analytical properties. Next, we investigate the stability of the game and propose a sufficient condition for the existence of the core.

In the beginning, we have the following lemma.

Lemma 1: Let

$$f(S) = \sum_{i \in S_m} u_i(S) + \sum_{j \in S_s} \tilde{u}_j(S)$$

denote the sum payoff of S . When $\gamma_j = 1$ and $\beta_i = 1$, we have

$$f(S) = \sum_{i \in S_m} \alpha_i T_i(S) - \sum_{j \in S_s} \mu_j C_j(S).$$

That is to say, the pricing has no effect on the sum payoff in this case.

Proof: First we can prove that

$$\chi_i = \sum_{j \in S_s} \eta_{ij}(S) \xi_{ji}.$$

Then

$$\begin{aligned} \mathbb{E}_\Psi \{1_{f_S(\Psi)=\{i\}}\} \chi_i &= \mathbb{E}_\Psi \{1_{f_S(\Psi)=\{i\}}\} \sum_{j \in S_s} \eta_{ij}(S) \xi_{ji} \\ &\stackrel{(a)}{=} \sum_{j \in S_s} \mathbb{E}_\Psi \{1_{f_S(\Psi)=\{i\}}\} \eta_{ij}(S) \xi_{ji}. \end{aligned} \quad (6)$$

(a) holds since $\mathbb{E}_\Psi \{1_{f_S(\Psi)=\{i\}}\}$ is irrelevant to $j \in S_s$. Next, based on (6), we can derive

$$\sum_{i \in S_m} \mathbb{E}_\Psi \{1_{f_S(\Psi)=\{i\}}\} \chi_i = \sum_{i \in S_m} \sum_{j \in S_s} \mathbb{E}_\Psi \{1_{f_S(\Psi)=\{i\}}\} \eta_{ij}(S) \xi_{ji}. \quad (7)$$

Exchanging the summation order on the right side, we get

$$\sum_{i \in S_u} P_i(S) = \sum_{j \in S_s} R_j(S). \quad (8)$$

When $\gamma_j = 1$ and $\beta_i = 1$,

$$f(S) = \sum_{i \in S_m} \alpha_i T_i(S) - \sum_{j \in S_s} \mu_j C_j(S) + \sum_{i \in S_m} P_i(S) - \sum_{j \in S_s} R_j(S). \quad (9)$$

Using (8), we derive

$$f(S) = \sum_{i \in S_m} \alpha_i T_i(S) - \sum_{j \in S_s} \mu_j C_j(S).$$

Remark: Lemma 1 reveals the fact that the total revenues obtained by the MEC servers equal to the payments of all the MDs.

In addition, we obtain the second lemma.

Lemma 2: A coalition S should have at least one MD. Otherwise, $\tilde{u}_i(S) = 0 = \tilde{u}_i(\{i\})$ and $v(S) = \mathbf{0}$. That is to say, when there are only the MEC servers, the MEC servers have no stimuli to form coalitions and each MEC server will act alone.

Proof: When $|S_m| = 0$, we get $R_j(S) = 0$ and $C_j(S) = 0$ according to (3) and (5), respectively. Thus, $\tilde{u}_i(S) = 0$. Specifically, $\tilde{u}_i(\{i\}) = 0$. As $\tilde{u}_i(S) = \tilde{u}_i(\{i\})$ in this case, each MEC server will act alone. ■

Remark: The function of the MEC server is pre-processing and forwarding the MD's signal. So when there is no MD, it is meaningless to group only the MEC servers together.

On the other hand, when there is no MEC server in a coalition S , i.e., $S \subseteq \mathfrak{M}$,

$$u_i(S) = \mathbb{E}_{\Psi} \{1_{f_S(\Psi)=\{i\}}\} * r_i * \prod_{j \in \mathfrak{M} \setminus S} (1 - p_j)$$

for $i \in S$ and $v(S) > 0$ if $r_i \neq 0$. Specially when $S = \{i\}$, we derive

$$u_i(\{i\}) = p_i r_i \prod_{j \in \mathfrak{M} \setminus \{i\}} (1 - p_j).$$

Hence, when $\exists S \subseteq \mathfrak{M} \ \& \ S \ni i$ satisfying $u_i(S) > u_i(\{i\})$, the MDs will form coalitions to improve the utility. Specifically, let $S = \{s_1, \dots, s_{|S|}\}$ with $s_1 > \dots > s_{|S|}$, based on (1) and (2), we can derive that if

$$1 \geq \begin{cases} \prod_{j \in S \setminus \{s_i\}} (1 - p_j), & i = |S|; \\ \frac{\prod_{j \in S \setminus \{s_i\}} (1 - p_j)}{\prod_{k=i+1}^{|S|} (1 - p_{s_k})}, & \text{otherwise,} \end{cases} \quad (10)$$

forming coalition S is profitable.³ Specially, when $p_i = p$, i.e., all MDs have the same active probability, we can derive that (10) holds, then forming coalitions is always profitable in the case. The reason is as follows: Since the formulation of coalitions can avoid collision, then it can improve the effective throughput of MDs.

The definition for the core of our coalitional game is given as follows.

Definition 1: The core of $(\mathfrak{M} \cup \mathfrak{S}, v)$ is defined as

$$C = \{x \in v(\mathfrak{M} \cup \mathfrak{S}) : \forall S, \nexists y \in v(S), \text{ s.t. } y_i > x_i, \forall i \in S\}.$$

The core existence represents the stability of the grand coalition, and the core is not always guaranteed to exist. The following lemma gives a sufficient condition for the existence of the core.

Lemma 3: The core of $(\mathfrak{M} \cup \mathfrak{S}, v)$ is nonempty once the following conditions hold ($S \subset \mathfrak{M} \cup \mathfrak{S}$): 1)

- 1) $\alpha_i > 0, \beta_i > 0, \gamma_j > 0$, and $\mu_j > 0$.
- 2) $\alpha_i T_i(S) > \beta_i P_i(S)$ or $\gamma_j R_j(S) > \mu_j C_j(S)$.
- 3) $\alpha_i T_i(\mathfrak{M} \cup \mathfrak{S}) - \beta_i P_i(\mathfrak{M} \cup \mathfrak{S}) > \alpha_i T_i(S) - \beta_i P_i(S)$, and $\gamma_j R_j(\mathfrak{M} \cup \mathfrak{S}) - \mu_j C_j(\mathfrak{M} \cup \mathfrak{S}) > \gamma_j R_j(S) - \mu_j C_j(S)$.

Proof: When 1) holds, we can find $\alpha_i, \beta_i, \gamma_i$, and μ_j to satisfy 2). If 2) does not hold, we have

$$u_i(\{i\}) = p_i r_i \prod_{j \in \mathfrak{M} \setminus \{i\}} (1 - p_j) \geq 0 \geq u_i(S)$$

for $i \in S_m$ and $\tilde{u}_j(S) \leq 0 = \tilde{u}_j(\{j\})$ for $j \in S_s$. Then, each MD and MEC server will act alone. In this case, the core is empty. When 3) holds, we can prove that $(\mathfrak{M} \cup \mathfrak{S}, v)$ is

³Although forming S may be not optimal, it is at least better than acting alone.

balanced [18]. Thus, the core is nonempty according to the Bondareva-Shapley theorem. ■

Remark: When the conditions of Lemma 3 hold, the core exists; that is to say, the grand coalition has the optimal "value". Generally, any possible coalition structures can be optimal. We just investigate the conditions for grand coalition's optimality here.

Remark: Avoiding transmission collisions and charging for offloading are imperative to motivate the MDs and MEC servers, respectively, to join the grand (or any other) coalition.

V. NUMERICAL RESULTS

In the numerical examples, we consider 2 MDs (MD 1 and MD 2) and 2 MEC servers (MEC-s 3 and MEC-s 4). Two dimensional scenario is considered. MDs are uniformly distributed in an 10×10 , where (5, 5) is its center, MEC-s 3 locates at (0, 0), MEC-s 4 locates at (7, 6). 10^6 topology implementations are averaged to get the mean performance.

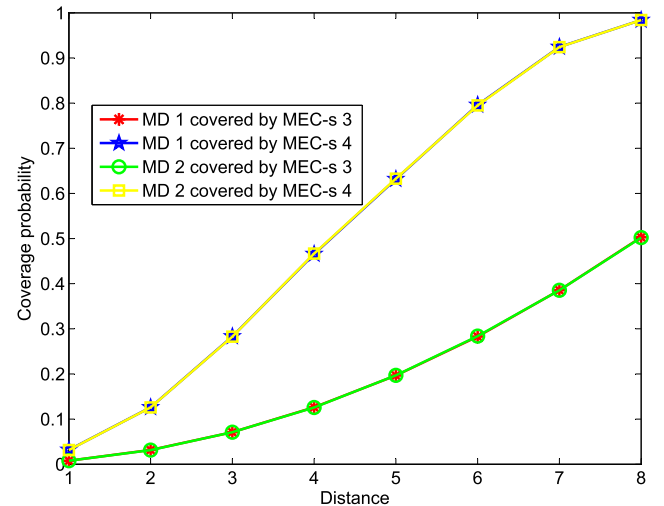


FIGURE 2. Coverage probability v.s. transmit distance, d .

Fig. 2 shows the probability of MD 1 and MD 2 being covered by MEC-s 3 and MEC-s 4, respectively. From the figure, we can find that the coverage probabilities of MEC-s 3 over MD 1 and MD 2 are same, and the coverage probabilities of MEC-s 4 over MD 1 and MD 2 are same also. In addition, the coverage probability of MEC-s 4 is higher than that of MEC-s 3 and both increase with the increase of d . We can explain by theoretical analysis. Since MD 1 and MD 2 are uniformly distributed, the coverage probability can be computed using Fig. 3 in two-dimensional case. For any MD, when it is in the overlap of a circle centering at (0, 0) with radius d , it can be coverage by MEC-s 3. Then, the coverage probability is the ratio between the area of the overlap and 10×10 . With the increase of d , the ratio increases (until it reaches 1). For the MEC-s 4, the center becomes (7, 6) and we can obtain similar results. Furthermore, as (7, 6) is nearer to (5, 5)

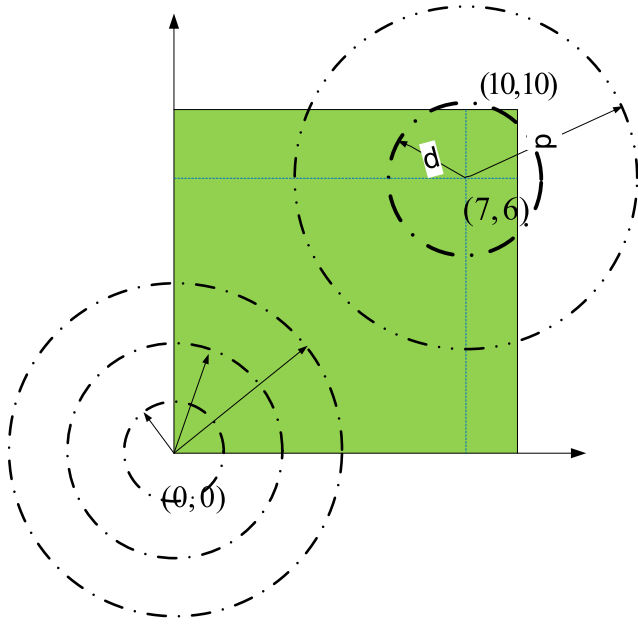


FIGURE 3. Theoretical computation of the coverage probability when MDs are uniformly distributed.

(i.e., area center) with the same d , its overlap area is bigger than that for $(0,0)$. Then the coverage probability of MEC-s 4 is higher than that of MEC-s 3.

TABLE 1. Possible coalition structures for 4 nodes.

$C_1: \{1,2,3,4\}$	$C_6: \{1,3\}, \{2,4\}$	$C_{11}: \{1,2\}, \{3,4\}$
$C_2: \{1,3,4\}, \{2\}$	$C_7: \{1,2,3\}, \{4\}$	$C_{12}: \{1\}, \{2\}, \{3,4\}$
$C_3: \{1,2\}, \{3\}, \{4\}$	$C_8: \{1\}, \{2,3,4\}$	$C_{13}: \{1,2,4\}, \{3\}$
$C_4: \{1\}, \{2\}, \{3\}, \{4\}$	$C_9: \{1,4\}, \{2,3\}$	$C_{14}: \{1,4\}, \{2\}, \{3\}$
$C_5: \{1\}, \{3\}, \{2,4\}$	$C_{10}: \{1\}, \{4\}, \{2,3\}$	$C_{15}: \{2\}, \{4\}, \{1,3\}$

There are 15 possible coalitional structures for 2-MD and 2-MEC-s, as listed in Table 1. Applying Lemma 2, C_{11} is similar as C_3 and C_{12} is similar as C_4 . Meanwhile, as MD 1 and MD 2 as well as MEC-s 3 and MEC-s 4 are role-exchangeable in the scheme, we can see that C_8 is similar as C_2 ; C_9 is similar as C_6 ; C_{10} , C_{14} and C_{15} are similar as C_5 ; and C_{13} is similar as C_7 . In conclusion, we need to consider $C_1 - C_7$. In the following simulations, $\mathcal{R}_i = 1.8$, $r_i = 1$, $\xi_i = 1.5$, $\alpha_i = 10$, $p_i = 0.6$, $c_{ji}^r = 0.2$, $c_{ji}^f = 0.5$, and $\beta_i = \gamma_i = \mu_i = 1$.

Fig. 4 plots the mean utility performance under C_1 , which is also referred to as the grand coalition, i.e., all nodes form one coalition. We can observe that the utility performance improves when the transmit distance becomes longer. It is because that with the expand of the transmit distance, the coverage probability increases. Then the MEC servers could take part in the data collection with higher probability, and the rate improves. The performance of MD 1 is better than that of MD 2 since MD 1 has priority in transmitting node selection in the scheme when MD 1 and MD 2 in the same coalition. MEC-s 4 has better coverage probability which leads to more revenues charged from MDs. Hence MEC-s 4 has better performance than MEC-s 3.

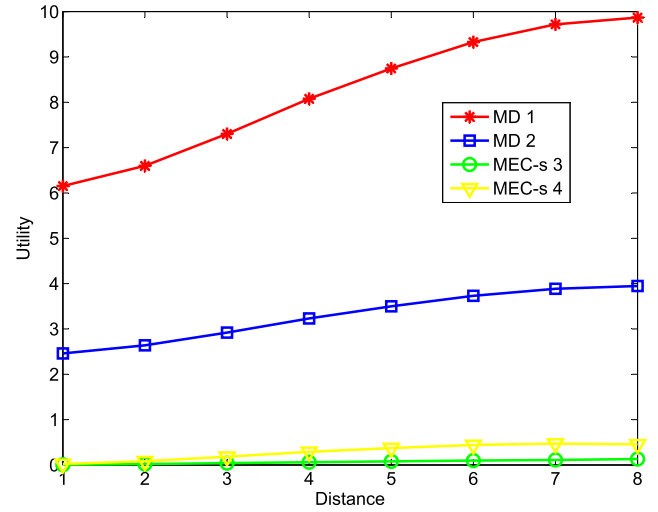


FIGURE 4. Mean utility of C_1 .

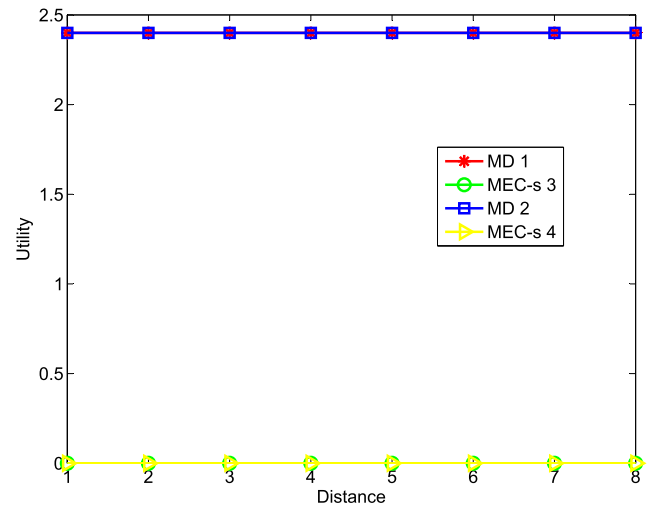
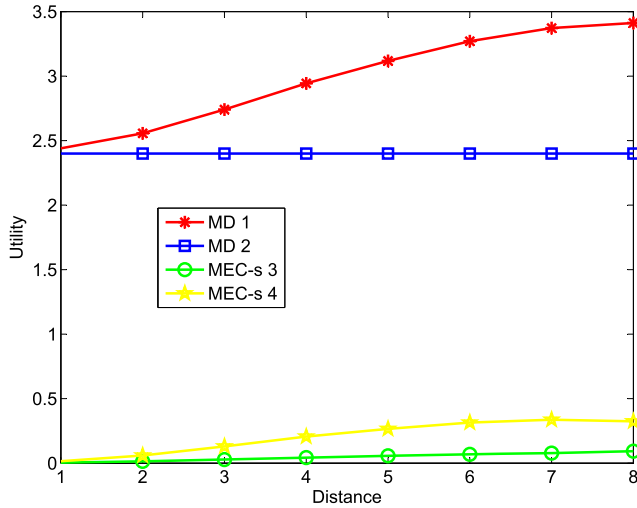
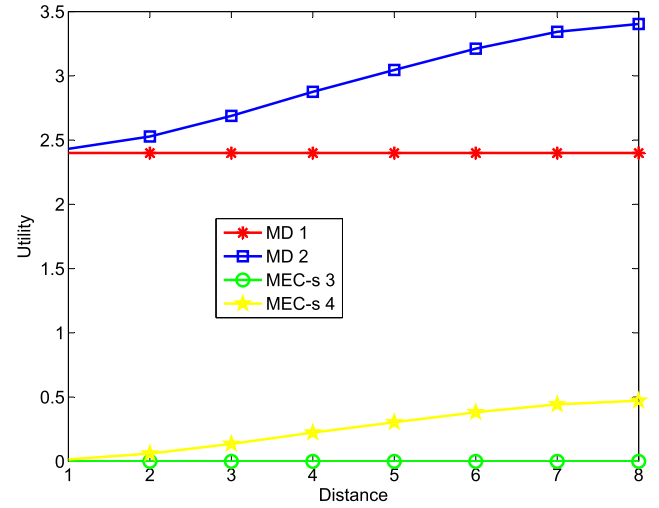
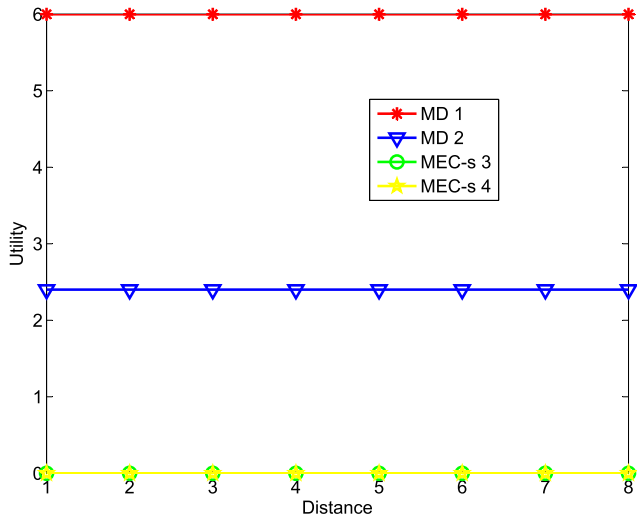
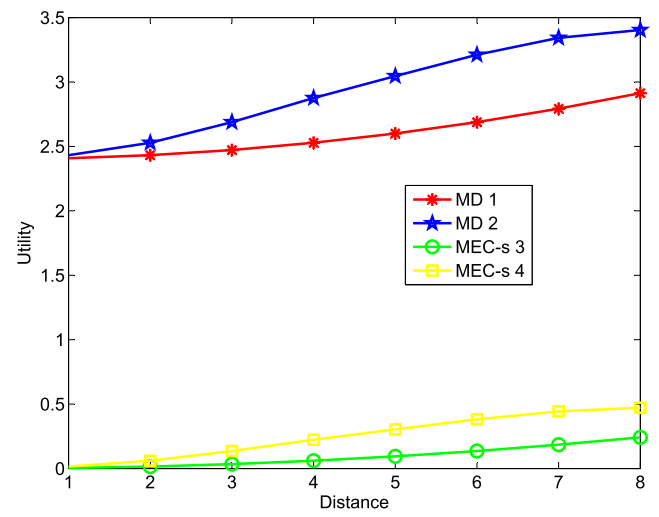


FIGURE 5. Mean utility of C_4 .

Fig. 5 demonstrates the mean utility performance under C_4 , where each node forms a coalition and transmit solely. We can find that the utility performance of MEC-s 3 and MEC-s 4 remains as zero. This can be explained by using Lemma 2. The utility performances of MD 1 and MD 2 are the same and remain constant. The C_4 can be viewed as a baseline.

Fig. 6 shows the mean utility performance under C_2 . MD 1, MEC-s 3, and MEC-s 4 are in a coalition. The performance improves with the increase of transmit distance. As MD 2 transmits solely, the utility remains constant with respect to transmit distance. The performance of MD 1 is better than that of MD 2. It verifies that the MEC could improve utility performance (especially by comparison with Fig. 5).

Fig. 7 illustrates the utility performance with C_3 . MEC-s 3 and MEC-s 4 respectively form a coalition. And the utility performance remains zero, which complies with Lemma 2. MD 1 and MD 2 form one coalition. Since no MEC-s available, the utility performances are constant. The performance

FIGURE 6. Mean utility of C_2 .FIGURE 8. Mean utility of C_5 .FIGURE 7. Mean utility of C_3 .FIGURE 9. Mean utility of C_6 .

of MD 1 is better than that of MD 2 because of its priority in transmit scheduling within the coalition. In addition, compared to Fig. 5, we can see the utility increase of MD 1. That is to say, even without MEC server, forming coalition is profitable for MD. This can be explained as follows: When forming coalition, collisions can be avoided. Then the effective throughput increases and utility improves accordingly.

Fig. 8 depicts the average utility performance under C_5 setting. MD 1 and MEC-s 3 respectively constitute a coalition. Then the utility performance remains constant. MD 2 and MEC-s 4 form one coalition, and the utility increases with transmit distance. Furthermore, MD 2 has better performance than MD 1 and MEC-4 has better performance than MEC-s 3. This verifies the advances of constituting coalition.

Fig. 9 draws the mean utility performance with C_6 . In the setting, MD 1 and MEC-s 3 form one coalition; MD 2 and MEC-s 4 constitute another coalition. Compared with Fig. 5, utility performance of each node has improvement.

Additionally, MD 2 has better performance than MD 1 and MEC-4 has better performance than MEC-s 3. This is because that MEC-s 4 has better coverage probability than MEC-s 3, then the MEC-s 4 & MD 2 coalition has better performance.

Fig. 10 plots the average utility performance under C_7 . MD 1, MD 2, and MEC-s 3 constitute one coalition. MEC-s 4 forms another coalition solely. Since MEC-s 4 act alone, its utility remains zero. MD 1 and MD 2 could utilize MEC-s 3 for MEC data transmission to the cloud server. Utility performance increases with increment of d since bigger value of d incurs higher coverage probability and transmission rate performance thereafter. MD 1 has better performance than MD 2 as MD 1 has selection priority in scheduling.

Comparing utility performances of the considered coalition structures, we find that the grand coalition, C_1 , has the best score. In addition, all utilities in the grand coalition are positive and $\alpha_i > 0$, $\beta_i = \gamma_i = \mu_i > 0$. Then the conditions

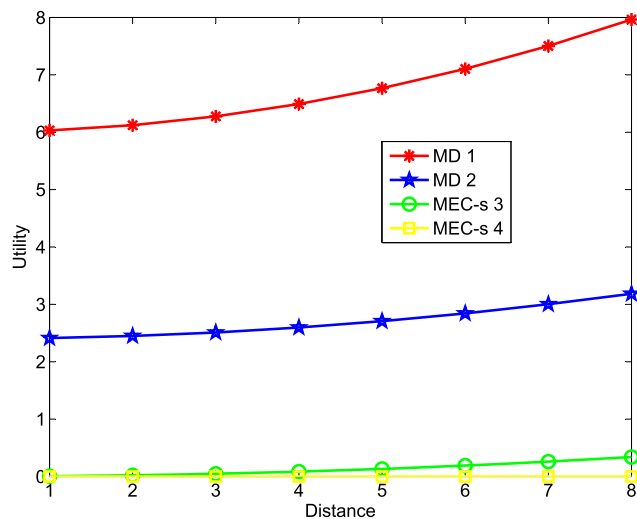


FIGURE 10. Mean utility of C_7 .

of Lemma 3 hold, we claim that the core is not empty and $(u_1(C_1), u_2(C_1), u_3(C_1), u_4(C_1))$ is in the core.

VI. CONCLUSION AND FUTURE WORK

Data offloading in multi-MD and multi-MEC-server scenario is studied in the paper. We propose a coalition based pricing scheme. The proposed scheme incorporates MD scheduling, MEC server selection, and offloading encouragement. A coalitional NTU game is formulated, and some theoretical properties are derived by analysis on the game thereafter. Especially, we give sufficient conditions for non-empty core. In the end, numerical results verify the effectiveness of the proposed scheme by showing the utility performance.

In this paper, we have proposed a data offloading scheme and investigated the performance in all possible coalition structures. There may be an optimal structure, and finding the optimal structure (e.g., by utilizing coalition formulation game theory) can be future work.

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