A Nash Bargaining Approach to Emergency Demand Response in Colocation Data Centers

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***Abstract*—Data centers are recognized as promising resources for emergency demand response (EDR) that requires a certain amount of power reduction when system reliability is in danger. In this paper, we study EDR in a colocation data center where multiple tenants deploy their own servers in a shared space managed by a data center operator. While the data center operator desires to reduce the usage of expensive and environmentally unfriendly backup generation during EDR events, the tenants who can control their servers have little incentive to reduce their power consumption. To enable cost-effective and eco-friendly EDR, the data center operator has to properly incentivize the tenants to modulate server power consumption. Furthermore, the social welfare generated during EDR should be properly shared among the data center operator and tenants so that all of them are satisfied. We propose an approach based on the Nash bargaining solution, which is Pareto efficient, fair and social welfare maximizing, to incentivize the tenants' participation and allocate the social welfare among the data center operator and tenants properly. Trace-driven simulations are conducted to demonstrate the effectiveness of our proposed approach.**

I. INTRODUCTION

Data centers, whose power demand is large yet flexible, are recognized as promising demand response resources [1]. Data centers are expanding in both numbers and scales to satisfy the increasing IT demand, which leads to significant power consumption. In 2013, data centers in U.S. alone consumed 91 billion kilowatt-hours of electricity, and this number is expected to increase about 10% annually [2]. Even though the large power consumption of data centers was regarded as a huge burden to the power grid traditionally, data centers have been recognized as promising yet under-utilized demand response resources recently. IT computing knobs [3], [4] and non-IT knobs [5], [6] make data center demand response technically and economically feasible. In summary, through data center demand response, data centers receive rewards and the power grid better balances the supply and demand in real time.

Emergency demand response (EDR), which is called under emergency situations such as extreme weather, is the most widely adopted demand response program. Across all reliability regions, EDR accounts for 87% demand reduction capability [7]. Large electricity consumers including data centers are coordinated under EDR to reduce their power consumption so as to prevent blackouts. Data centers, as large yet flexible loads, have been regarded as important resources for EDR by U.S. EPA [8]. Traditionally, data centers participate into EDR by starting up their on-site backup generators such as diesel generators, which is both expensive and environmentally unfriendly. Nowadays, data centers intend to participate into EDR by modulating server power consumption as explored by several recent works [9], [10], which is more cost-effective and environmentally friendly. However, the literature mentioned above mostly focuses on owner-operated data centers (e.g., Google data centers), whose techniques may not be directly applicable to other types of data centers.

Colocation data centers (simply called colos), which rent out spaces to multiple tenants to house their own servers, are an important but under-explored type of data center. In a colo, the colo operator is only responsible for facility support and has no control over the servers housed in the colo. There are more than 1200 colos in US [11], and they account for 40% of the total energy consumption in data center industry [2]. Furthermore, colos are mostly located in urban areas such as New York and Silicon Valley which are residential intensive. Since EDR is more likely to be called in these areas, colos can provide a higher potential for peak power reduction than owner-operated data centers which are usually located in rural areas.

Considering colo EDR, we need to address the split incentive challenge: while the colo operator desires satisfying EDR without relying on on-site backup generation, tenants who have control over their servers have little or even no incentive to behave in the interest of the colo operator since they are usually charged based on their subscribed peak/reserved power. Hence, it is far from easy for colos to participate into EDR due to the uncoordinated power management in colos. To enable economic and environmentally friendly colo EDR, the colo operator has to incentivize the tenants to reduce their power consumption, which motivates the incentive mechanism design for colo EDR. Bidding based incentive mechanism design has been studied in [12]–[14]. However, the results of bidding based mechanisms highly depend on the auctioneer selection. Moreover, the existing works study the incentive mechanism design in a non-cooperative manner, and thus cannot model the cooperation between the colo operator and

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the tenants.

In this paper, we investigate how the colo operator should incentivize the tenants to reduce their power consumption during EDR, and how the social welfare generated during EDR should be shared by the colo operator and the tenants under the concurrent bargaining protocol. Our proposed approach is based on the Nash bargaining solution (NBS) [15]–[17]: once the colo operator receives the EDR target, the colo operator initiates bargaining with the tenants to negotiate the reimbursements offered to the tenants and the amount of power reduction from the tenants. The proposed approach is self-enforcing, i.e., both the tenants and the colo operator have the right to reject any outcome that impairs its profit so that a mutual beneficial outcome can be reached. The outcome, i.e., the reimbursement and the power reduction, must be approved by both the colo operator and the tenants. We quantify the gains of the colo operator and the tenants, and analyze the connection between the NBS and the social welfare maximization problem. We prove that our proposed approach satisfies Pareto efficiency, max-min fairness and solves the social welfare maximization problem.

The remainder of this paper is organized as follows. First, we describe the system model in Section II. Next, we analyze the NBS under the concurrent bargaining in Section III. Then, we show the performance evaluation in Section IV. Finally, we conclude the paper in Section V.

II. System Model

We consider a colo operated by a colo operator with $\mathcal{N} = \{1, 2, \cdots, N\}$ tenants. Each tenant $i \in \mathcal{N}$, who subscribes a peak power usage from the colo operator, has M_i homogeneous servers. The colo operator is responsible for facility support such as cooling and security. The utility company issues the EDR signal to the colo operator, indicating a certain amount of power reduction D from the colo. The EDR target D is mandatory and must be satisfied during the EDR event. Traditionally, the colo operator will start up its on-site backup generator to satisfy the EDR target, which is expensive and environmentally unfriendly. We focus on EDR for a single time slot in this paper.

A. Tenants

Power consumption model. Denote the idle power and peak power of the servers of tenant i as P_i^{idle} and P_i^{peak}, respectively. Using the power consumption model [18], the average power consumption of tenant i when x servers are kept active can be represented as

$$P_i(x) = x\left[P_i^{\text{idle}} + u_i(P_i^{\text{peak}} - P_i^{\text{idle}})\right], \tag{1}$$

where u_i is the average CPU utilization level. Assume M/GI/1 Processor Sharing (PS) model is adopted at each server [4]. Denote the average arrival rate of workload and the service rate of a server as λ_i and μ_i, respectively. Then the average CPU utilization level is $u_i = \lambda_i/(\mu_i x)$.

We assume that all M_i servers are kept active when tenant i does not participate into EDR programs. Assume that the tenants will turn off the unused servers when participating into EDR programs to reduce their power consumption. From (1), we can obtain that the power reduction of tenant i when turning off m_i servers is

$$\Delta P_i = m_i P_i^{\text{idle}}. \tag{2}$$

Since data centers usually contain thousands of servers, without loss of generality we relax the constraint that m_i is integer and regard ΔP_i as continuous.

QoS constraint model. In this paper, we use the response delay suffered by tenants after turning off unused servers to quantify the quality of service (QoS) constraint which is used to bound the maximum number of servers that can be turned off. Denote $T_i^{\max}$ as the maximum average delay of the workload that can be tolerated by tenant i. Then using the queueing theory [19], the average processing delay is characterized as $T_i = \frac{1}{\mu_i - \lambda_i/(M_i - m_i)} \le T_i^{\max}$. Hence, it is straightforward to obtain that the number of the servers that can be turned off is bounded as $0 \le m_i \le M_i - \frac{\lambda_i}{\mu_i - 1/T_i^{\max}}$. Therefore, the power reduction offered by each tenant i should satisfy the following constraint:

$$0 \le \Delta P_i \le \Delta P_i^{\max}, \tag{3}$$

where $\Delta P_i^{\max} = P_i^{\text{idle}}\left(M_i - \frac{\lambda_i}{\mu_i - 1/T_i^{\max}}\right)$.

Inconvenience cost model. Tenants that turn off servers will incur inconvenience cost due to performance degradation. In this paper, we do not specify what type of inconvenience cost is imposed to the tenants. However, we make the following general assumption on the inconvenience cost.

Assumption 1. *For each tenant $i \in \mathcal{N}$, the inconvenience cost function $C_i(\Delta P_i)$ is convex, strictly increasing and differentiable over the domain $0 \le \Delta P_i \le \Delta P_i^{max}$, with $C_i(\Delta P_i) = 0$ when $\Delta P_i = 0$.*

We denote the first-order derivative of the cost function $C_i(\Delta P_i)$ as $C_i'(\Delta P_i)$, whose inverse function is denoted as $C_i'^{-1}(\Delta P_i)$.

Tenant utility model. Each tenant i will be rewarded when reducing its power consumption. Denote the reward received by tenant i as r_i by reducing ΔP_i power consumption. Then the utility of tenant i can be represented as

$$U_i(r_i, \Delta P_i) = r_i - C_i(\Delta P_i). \tag{4}$$

In the following, we assume that each tenant i will interact with the colo operator by revealing its total power reduction ΔP_i.

B. Colo Operator

First, consider the scenario that no tenant is willing to reduce its power consumption during the EDR event. Therefore, to satisfy the power reduction target D issued by the utility company, the colo operator has to start up its on-site backup generator, which is neither economic nor environmentally friendly. In this case, without loss of generality, we model the cost incurred by the colo operator as a linear function

$G^0 = \alpha D$, where α is the unit on-site generation cost. Here we assume that the on-site generator has a sufficiently large capacity to satisfy the EDR target D.

Fortunately, if the tenants can be properly incentivized to reduce their power consumption, the cost incurred by the colo operator can be reduced significantly. To capture the total power consumption of the colo including both the IT part and the non-IT part, we adopt power usage effectiveness (PUE) γ, which is defined as the ratio of the total power consumption to the IT power consumption. Then the cost of the colo operator with the participation of the tenants can be represented as

$$G(\mathbf{r}, \mathbf{\Delta P}) = \alpha \left(D - \gamma \sum_{i=1}^{N} \Delta P_i \right)^+ + \sum_{i=1}^{N} r_i, \tag{5}$$

where $\mathbf{\Delta P} = [\Delta P_1, \Delta P_2, \cdots, \Delta P_N]$ is the vector containing the power reduction amount of all tenants, $\mathbf{r} = [r_1, r_2, \cdots, r_N]$ is the vector containing the rewards issued to all tenants, and $(x)^+ = \max\{x, 0\}$. Note that (5) implies that the minimum power reduction from the colo must satisfy the target D during the EDR event. When the total power reduction from the tenants $\sum_{i=1}^{N} \Delta P_i$ cannot satisfy the EDR target D, the colo operator has to start up its on-site generator to satisfy the remaining $D - \sum_{i=1}^{N} \Delta P_i$ power reduction target.

Define the utility function of the colo operator as the cost saving with the tenants' participation into EDR. Then the utility of the colo operator is as follows:

$$\begin{aligned} V(\mathbf{r}, \mathbf{\Delta P}) &= G^0 - G(\mathbf{r}, \mathbf{\Delta P}) \\ &= \alpha \min \left\{ D, \gamma \sum_{i=1}^{N} \Delta P_i \right\} - \sum_{i=1}^{N} r_i. \end{aligned} \tag{6}$$

Two observations can be made from (6). First, if the reward issued to each tenant can be properly designed, the colo operator can save significant cost when participating into EDR programs. Next, we can see that the colo operator cannot obtain extra utility when the total power reduction of the tenants exceeds the EDR target D, i.e., the utility of the colo operator is limited by the minimum between the EDR target and the total power reduction of the tenants. Therefore, any proposal implying a power reduction that is larger than the EDR target will be not be compensated by the colo operator.

C. Social Welfare

The social welfare, which is defined as the sum of the utilities of tenants and the colo operator, is a widely adopted objective in mechanism design. Denote the social welfare as $\Psi(\mathbf{\Delta P})$. Then it can be calculated as

$$\begin{aligned} \Psi(\mathbf{\Delta P}) &= \sum_{i=1}^{N} U_i(r_i, \Delta P_i) + V(\mathbf{r}, \mathbf{\Delta P}) \\ &= \alpha \min \left\{ D, \gamma \sum_{i=1}^{N} \Delta P_i \right\} - \sum_{i=1}^{N} C_i(\Delta P_i). \end{aligned} \tag{7}$$

Since the reward issued to each tenant is cancelled out in the equation above, the social welfare $\Psi(\mathbf{\Delta P})$ is only dependent on each tenant's power reduction, which is determined by the number of servers it turns off as shown in (2) .

Social welfare is usually adopted to evaluate the welfare of resource allocation at the system-wide level in economics. In our case, to evaluate the performance of the power reduction profile $\mathbf{\Delta P}$ at the aggregate level, i.e., the colo level, we are interested in the social welfare maximization problem which is defined as

$$\max_{\mathbf{\Delta P}} \quad \alpha \min \left\{ D, \gamma \sum_{i=1}^{N} \Delta P_i \right\} - \sum_{i=1}^{N} C_i(\Delta P_i) \tag{8}$$

$$\text{s.t.} \quad 0 \leq \Delta P_i \leq \Delta P_i^{\max}, \ \forall i. \tag{9}$$

Note that based on Assumption 1, the social welfare maximization problem has a unique solution $\mathbf{\Delta P}$.

III. Nash Bargaining Solutions

To incentivize the tenants to participate into EDR, the colo operator will initiate the bargaining with the tenants, expecting to determine the power reductions from tenants $\mathbf{\Delta P}$ and the rewards the colo operator should offer $\mathbf{r}$. Intuitively, the tenant reducing more power consumption should receive a higher reward. The bargaining theory addresses the conflicts of the interest among the colo operator and tenants. If the colo operator and a tenant i determine a mutual beneficial solution $(r_i^*, \Delta P_i^*)$ where the individual rationalities of both the colo operator and the tenant are guaranteed, we say the colo operator and tenant i reach an agreement. Note that the agreement cannot be imposed to either the colo operator or the tenant without its approval. On the contrary, if the colo operator is not willing to offer any reward to tenant i or tenant i is not willing to reduce its power consumption, we say the colo operator and tenant i reach an disagreement. Under the disagreement case, the reward and the power reduction are both zero.

In the remainder of this section, we analyze the bargaining between the colo operator and the tenants. First, we introduce the background on the NBS, and start with our analysis on the NBS with a one-to-one bargaining case. Then we analyze the NBS of the generalized one-to-many bargaining.

A. One-to-One Bargaining

We consider the one-to-one bargaining case where the tenant set $\mathcal{N} = \{i\}$. To incentivize the tenant's participation into EDR, the colo operator bargains with the tenant to determine the power reduction amount of the tenant and the corresponding reward. We first consider that the bargaining ends at the disagreement point $(r_i^0, \Delta P_i^0) = (0, 0)$. The utilities of the colo operator and the tenant i at the disagreement point are denoted as $V^0 = 0$ and $U_i^0 = 0$, respectively. Next, consider the colo operator and the tenant reach an agreement. Then the payoffs obtained by the tenant and the colo operator are calculated based on (4) and (6), respectively. The NBS of the one-to-one bargaining between the colo operator and tenant i

can be obtained by solving the following optimization problem [16], [17]:

$$\max_{r_i,\Delta P_i} \quad \left(U_i(r_i,\Delta P_i)-U_i^0\right)\left(V(r_i,\Delta P_i)-V^0\right) \tag{10}$$
$$\text{s.t.} \quad U(r_i,\Delta P_i)-U_i^0\geq 0, \tag{11}$$
$$V(r_i,\Delta P_i)-V^0\geq 0, \tag{12}$$
$$r_i\geq 0, \tag{13}$$
$$0\leq \Delta P_i\leq \Delta P_i^{\max}. \tag{14}$$

We describe the NBS under the one-to-one bargaining case in the following lemma.

Lemma 1. *The optimal power reduction of tenant i under the one-to-one bargaining is*

$$\Delta P_i^* = \min\left\{D/\gamma, \Delta P_i^{max}, C_i'^{-1}(\alpha\gamma)\right\}, \tag{15}$$

The corresponding optimal reward of tenant i under the one-to-one bargaining is

$$r_i^* = \frac{\alpha\min\{D,\gamma\Delta P_i^*\}+C_i(\Delta P_i)}{2}. \tag{16}$$

Proof: Taking the logarithm of the objective function (10), we can see that the one-to-one bargaining problem has a unique solution due to its concavity. We define an auxiliary variable $\tau=\min\{D,\gamma\Delta P_i\}$. Then we rewrite the one-to-one bargaining problem using the auxiliary variable as follows:

$$\begin{aligned}\max_{r_i,\Delta P_i} \quad & (\alpha\tau-r_i)\left(r_i-C_i(\Delta P_i)\right)\\ \text{s.t.} \quad & \alpha\tau-r_i\geq 0,\\ & r_i-C_i(\Delta P_i)\geq 0,\\ & r_i\geq 0,\\ & 0\leq\Delta P_i\leq\Delta P_i^{\max},\\ & \tau\leq D,\\ & \tau\leq\gamma\Delta P_i.\end{aligned}$$

Next we can verify our solution by checking the KKT conditions of the optimization problem above under the following three cases.

1) If the optimization problem is unconstrained, we can obtain that $\Delta P_i^* = C_i'^{-1}(\alpha\gamma)$ using the first order optimality condition.
2) If $D<\min\{C_i'^{-1}(\alpha\gamma),\Delta P_i^{\max}\}$, then we can see that the utilities of the colo operator and the tenant increase over the domain $\Delta P_i\in[0,D/\gamma]$. Therefore, the optimal power reduction is $\Delta P_i^*=D/\gamma$.
3) If $\Delta P_i^{\max}<\min\{C_i'^{-1}(\alpha\gamma),D/\gamma\}$, similarly we can see that the utilities of the colo operator and the tenant increase over the domain $\Delta P_i\in[0,\Delta P_i^{\max}]$. Therefore, the optimal power reduction is $\Delta P_i^*=\Delta P_i^{\max}$.

Next, given any optimal power reduction ΔP_i, we can prove (16) using the first-order optimality conditions with respect to r_i. ■

B. Concurrent Bargaining

Based on the one-to-one bargaining mentioned before, in the following, we derive the general one-to-many NBS under the concurrent bargaining, and analyze the connection between the NBS and the social welfare maximization problem. In this case, all tenants bargain with the colo operator concurrently. The insight of the concurrent bargaining is that N one-to-one bargainings happen simultaneously. In the following, we first describe the bargaining protocol. Then we analyze the NBS under this protocol.

We start with the analysis of the solution under disagreement. For each tenant $i\in\mathcal{N}$, if the colo operator and the tenant cannot reach an agreement, the tenant will not turn off any server for power reduction and thus receive no payment from the colo operator, i.e., $r_i^0=0$, and $\Delta P_i^0=0$. Then the utility of the tenant under the disagreement is zero, i.e., $U_i^0=0$. For the colo operator, its utility under the disagreement at the worst-case scenario (i.e., no agreement is reached between the colo operator and any tenant, and the colo operator has to use its on-site generator to satisfy the EDR target D) is also zero.

Next consider the case that a tenant $i\in\mathcal{N}$ and the colo operator reach an agreement $(r_i,\Delta P_i)$. Then the utility of tenant i is represented as

$$U_i(r_i,\Delta P_i)=r_i-C_i(\Delta P_i). \tag{17}$$

The utility of the colo operator can be obtained by considering the case that it finishes the bargaining with all tenants, which is calculated as follows:

$$V(\mathbf{r},\mathbf{\Delta P})=\alpha\min\left\{D,\gamma\sum_{i=1}^{N}\Delta P_i\right\}-\sum_{i=1}^{N}r_i. \tag{18}$$

Since the utilities of the colo operator and tenants under the disagreement are zero, (17) and (18) also represent the utility gains of the tenants and the colo operator, respectively. Therefore, we can obtain the NBS under the concurrent bargaining by solving the following optimization problem:

$$\max_{\mathbf{r},\mathbf{\Delta P}} \quad V(\mathbf{r},\mathbf{\Delta P})\prod_{i=1}^{N}U_i(r_i,\Delta P_i) \tag{19}$$
$$\text{s.t.} \quad U_i(r_i,\Delta P_i)\geq 0,\ \forall i \tag{20}$$
$$V(\mathbf{r}_i,\mathbf{\Delta P}_i)-V^0\geq 0,\ \forall i \tag{21}$$
$$r_i\geq 0,\ \forall i \tag{22}$$
$$0\leq\Delta P_i\leq\Delta P_i^{\max},\ \forall i. \tag{23}$$

We describe the NBS under the concurrent bargaining in the following lemma.

Lemma 2. *Given the power reduction of the other $N-1$ tenants $\Delta P_j^*,\ \forall j\in\mathcal{N}\setminus\{i\}$, the power reduction of tenant i is*

$$\Delta P_i^*=\min\left\{D/\gamma-\sum_{j\in\mathcal{N}\setminus\{i\}}\Delta P_j^*,\Delta P_i^{\max},C_i'^{-1}(\alpha\gamma)\right\}. \tag{24}$$

The corresponding reward issued to tenant n for reducing its power consumption is

$$r_i^* = C_i(\Delta P_i^*) + \frac{1}{N'+1}\left[\alpha \min\left\{D, \gamma \sum_{j=1}^{N} \Delta P_j^*\right\} - \sum_{j=1}^{N} C_j(\Delta P_j^*)\right], \quad (25)$$

where N' denotes the number of tenants that participate into EDR.

Proof: First, note that the concurrent bargaining problem is concave and thus has a unique solution. Similar to the proof of Lemma 1, to prove (24) holds, we introduce an auxiliary variable $\delta = \min\left\{D - \gamma \sum_{j \in \mathcal{N}\setminus\{i\}} \Delta P_j^*, \Delta P_i\right\}$, rewrite the concurrent bargaining problem, and then check the KKT conditions of the derived optimization problem. First, we take the logarithm of the objective function (19) as

$$\log\left(V(\mathbf{r}, \mathbf{\Delta P})\right) + \sum_{i=1}^{N} \log\left(U_i(r_i, \Delta P_i)\right). \quad (26)$$

Given the power reduction profile $\mathbf{\Delta P}$, we solve the set of equations obtained using the first-order optimality conditions with respect to $r_i, \forall i$:

$$\sum_{i=1}^{N} r_i = \frac{1}{N'+1} \sum_{i=1}^{N} C_i(\Delta P_i) + \frac{N'}{N'+1} \alpha \min\left\{D, \gamma \sum_{i=1}^{N} \Delta P_i\right\}. \quad (27)$$

Substituting (27) into our original optimization problem, we can see that (24) and (25) hold. ■

In the following, we briefly discuss the properties of our proposed solution.

Individual rationality. From (25), we observe that the reward should compensate the inconvenience cost incurred by the tenant during the EDR event. Therefore, the tenant should receive non-negative utility, implying that individual rationality is satisfied.

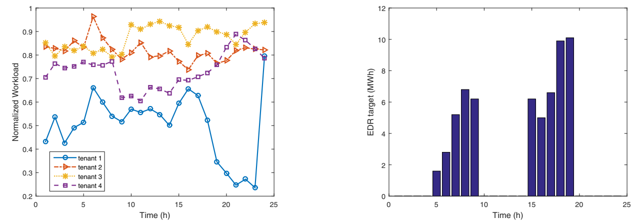
Max-min fairness. From (25), we observe that the utility of each tenant is $1/(N'+1)$ fraction of the social welfare, which equals to the utility of the colo operator. Therefore, the colo operator and all tenants have equitable utility gains under the concurrent bargaining, and thus our proposed approach satisfies the max-min fairness property.

Social welfare maximization. We show the relationship between the NBS and the social welfare maximization problem in the following theorem.

Theorem 1. *The NBS under the concurrent bargaining maximizes the social welfare $\Psi(\mathbf{\Delta P})$, i.e.,*

$$\mathbf{\Delta P}^* = \underset{\mathbf{\Delta P}}{\operatorname{argmax}}\ \Psi(\mathbf{\Delta P}). \quad (28)$$

Proof: Note that both the social welfare maximization problem and the concurrent bargaining problem have a unique



(a) (b)

Fig. 1: (a) Typical one day workload traces of 4 tenants; (b) EDR reduction target.

power reduction solution. Based on Lemma 2, we substitute the rewards in the objective function (19) with (25). Then we can observe that the derived objective function is equivalent to that of the social welfare maximization. ■

Pareto efficiency. Based on Lemma 2 and Theorem 1, we can see that the social welfare is shared by the colo operator and tenants in a Pareto efficient manner, i.e., no player including the colo operator and all tenants can improve its utility without impairing other players' utilities.

IV. Performance Evaluation

A. Simulation Setup

Colocation data center setup. We consider a colo with 4 tenants located at Ashburn, VA, which is a major data center market served by PJM interconnection [20]. Each tenant has $M_i = 2000$ homogenous servers, whose idle and peak power are set as $P_i^{\text{idle}} = 150$W and $P_i^{\text{peak}} = 250$W, respectively. We set the PUE of the colo as $\gamma = 1.5$. Therefore, the corresponding power reduction of colo from tenant i is 1.5kW if the tenant reduces 1kW power consumption. The colo has a diesel generator, whose unit cost is $\alpha = \$0.5$/kWh. The colo will participate into EDR following the EDR signals issued by PJM interconnection.

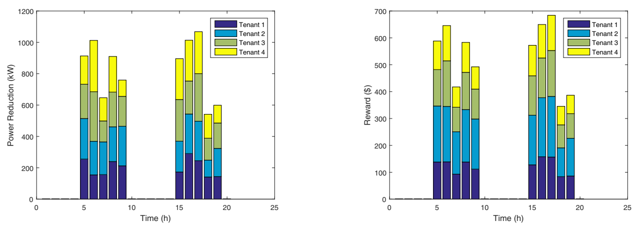
Tenant workload description. We use the trace data of Google cluster as the workloads of the tenants [21]. All workloads have been normalized with respect to the maximum service capacity of each tenant. The normalized workloads are depicted in Fig. 1a.

Tenants' cost. The inconvenience cost of each tenant might include the delay cost and the wear and tear cost. Without loss of generality, we focus on the wear-and-tear cost and use a linear function to model it:

$$C_i(\Delta P_i) = w_i \Delta P_i, \ \forall i \in \mathcal{N}, \quad (29)$$

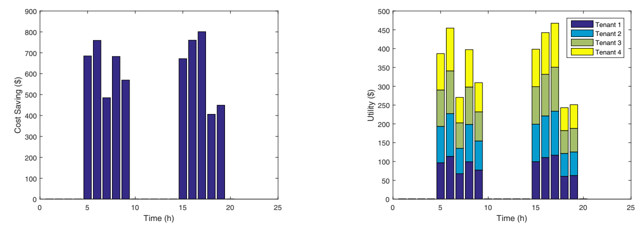
where w_i denotes the unit wear and tear cost and is set to be uniformly distributed in $(\$0, \$0.6]$/kWh.

EDR setup. We use the EDR signals issued by PJM interconnection on January 22, 2014 for our simulations. The EDR target at each hour is depicted in Fig. 1b. As shown in Fig. 1b, there are ten EDR events with each lasting one hour. The EDR started from 5am to 9am and 3pm to 7pm.



(a) (b)

Fig. 2: (a) Power reduction profile under the concurrent bargaining; (b) Rewards issued to the tenants under the concurrent bargaining.



(a) (b)

Fig. 3: (a) Cost saving of the colo operator when incentivizing tenants' participation; (b) Utilities of the tenants under the concurrent bargaining.

B. Simulation Results

Optimal power reduction and reward. In Fig. 2, we show the NBS under the concurrent bargaining. Specifically, we show the optimal power reduction and the corresponding rewards in Fig. 2a and Fig. 2b, respectively. In Fig. 2a, we show the power reduction contributed by all tenants at each hour. Since the colo operator will start up its on-site generator when the power reduction from the tenants cannot satisfy the EDR target, the EDR target will always be satisfied. Moreover, using the power reduction profile shown in Fig. 2a, the social welfare is maximized. The corresponding rewards issued to the tenants are depicted in Fig. 2b.

Utility analysis. According to our analysis before, the utility of the colo operator is its cost saving when incentivizing tenants' participation into EDR, while the utilities of the tenants are their profits when participating into EDR. In Fig. 3, we show the utility obtained by the colo operator and the utilities of the tenants in Fig. 3a and Fig. 3b, respectively. We have four observations from Fig. 3. First, we can observe that by incentivizing the tenants to participate into EDR, the colo operator saves significant cost. Therefore, the individual rationality of the colo operator is guaranteed using our proposed approach. Next, since the utilities received by all tenants are non-negative, the individual rationalities are guaranteed using our proposed approach. Furthermore, as shown in Fig. 3b, all tenants receive the same net utilities at each hour, which matches our analysis as shown in (25), i.e., the social welfare is equally shared by all the participants of EDR. Finally, we can see the colo operator and each tenant have equitable utility gains, which implies that our proposed approach satisfies the max-min fairness property.

V. Conclusion

This paper investigates how to incentivize the tenants to participate into colo EDR, and how the social welfare generated during EDR should be shared by the colo operator and tenants. We have proposed an approach based on the Nash bargaining solution, which is proved to be Pareto efficient, max-min fair and social welfare maximizing, to coordinate the tenants participating into EDR. Trace-driven simulations have been conducted to demonstrate our theoretical analysis, which shows that both the colo operator saves significant cost and the tenants receive rewards when participating into EDR.

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